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Uncertainty and Sensitivity Analyses of Ballast Life-Cycle Cost and Payback Period

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1. ABSTRACT

This paper introduces an innovative methodology for evaluating the relative significance of energy-efficient technologies applied to fluorescent lamp ballasts. The method involves replacing the point estimates of life cycle cost of the ballasts with uncertainty distributions reflecting the whole spectrum of possible costs, and the assessed probability associated with each value. We first examine the overall impact of variations of input variables to output variables such as Life-Cycle Cost (LCC) and payback time through the established analytical models for a specific product class - two ballasts operating two Lamp F40T12/ES lamps. The study then investigates the extent to which each input variable affects the outputs using the importance assessment and the sensitivity analysis. Finally, we revise the input distributions that

are proven to be more influential on the output than other inputs and refine the analysis. The results of uncertainty and sensitivity analyses will help analysts reduce effort in data collection and carry on analysis more efficiently. These methods also enable policymakers to gain an insightful understanding of which efficient technology alternatives benefit or cost what fraction of consumers, given the explicit assumptions of the analysis.

2. INTRODUCTION

Studies of the impacts of energy-efficient technology on appliance energy consumption have played an important role in aiding federal and state regulators develop appliance and lighting efficiency standards, and assess the expected economic impacts of proposed standards on consumers and manufacturers. The procedure for establishing federal standards is managed by the U.S. Department of Energy, and requires a thorough evaluation to ensure that any new or amended standard achieve the maximum improvement in energy efficiency that is determined to be technologically feasible and economically justified. The law requires a number of economic factors to be considered, among which are the economic impact on manufacturers and consumers, and the savings in lifetime operating costs compared with the increase in product price [NAECA 1987].

Two parameters that provide a measure of the benefit or cost to consumers of new energy-efficient technologies are their life cycle costs (LCC) and payback times. Life cycle cost is defined as the initial cost to the consumer, plus energy costs and other costs of operation and maintenance over the lifetime of the technology, discounted to present value. Payback time is the time in years required for an energy-efficient technology's savings in energy and other operating costs to equal the incremental cost of the efficient technology over the baseline technology. A reduced life cycle cost of an energy-efficient technology as compared to the baseline technology assumed by the study provides an important economic justification for energy efficiency standards incorporating the new technology.

However, developing convincing estimates of LCCs for existing and new energy-efficient technologies requires addressing a number of concerns. Many variables can have some effect on LCC, but not all of these have an equally large effect. Modeling the LCC of a technology can require gathering data on a dozen or more such variables. For example, electronic ballast technology examined in this paper can require data on up to 14 variables for LCC, and 12 variables for payback time.[1] Without special tools, the technology assessor does not know which of these variables contribute significantly to uncertainty in the result, and which have little or no effect.

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[1] Among the fourteen variables in the LCC calculations, four of them are fixed values, one is a scenario variable, and the rest are defined as probabilistic distributions. The variables for the LCC, but not for payback are: discount rate and ballast lifetime.

Compounding this difficulty is the problem of data availability and reliability. For some variables, data may be widely available; for others, the sources may be poor or nonexistent, requiring the modeler to make guesses, or extensive efforts to fill the gap. A tool to help the modeler identify the variables with little or no influence on LCC, payback time and other widely used indicators would help reduce analysis time and wasted effort, and increase confidence in the final assessment. Identifying those variables which are significant but for which little data are available would tell the investigator where to focus data-gathering resources; knowing that a variable is a less significant contributor to the output indicator can mean that existing data is sufficient input to the model even though it may be incomplete.

This paper discusses three steps for examining the relative significance of technology-specific input variables to output variables such as LCC and payback time for energy-efficient technologies: the overall uncertainty assessment, importance analysis, and the sensitivity analysis. We apply these methodologies, and show how they can be used to analyze the uncertainty and variability of inputs, in this case, for two-lamp fluorescent lamp ballast systems common in the commercial sector. Then we discuss how the results of uncertainty and sensitivity analyses provide useful information to policymakers concerning which efficient technology alternatives cost the consumer more or less, given the explicit assumptions of the analysis.

Uncertainty analysis refers to the determination of the overall variation in an output due to the collective effect of inputs that either are not completely known or vary with individual data points through a quantitative model, and the relative impacts of inputs on the output [Morgan and Henrion, 1990]. An example of an uncertain input, in this study, is lifetime of the fluorescent lamp ballasts—the exact value of average ballast lifetime is uncertain because the distribution of values is not completely known, even though some data points from this distribution are known. This is often designated as a Type B uncertainty [Hoffman and Hammonds 1994]. Type A uncertainty, also referred to as variability (or heterogeneity), is explained below.

The overall uncertainty analysis can provide some measure of how wide are the range of outputs. It reflects the whole spectrum of possible true values of the outputs, and the assessed probability associated with each value. However, it does not tell us how to identify the input variables that have the largest effects on the output variables. Using importance assessment by calculating rank order correlation between each individual input and the output, we are able to partition the overall variation in output among the input variables. In the example described in this paper, the importance assessment determines that electricity price, ballast life, and annual lighting hours have the largest effect of nine variables on total LCC and LCC saving (change of total LCC from the baseline to design options). It provides a method of winnowing out the most significant variables from a set.

Having conducted the importance assessment to determine which of the input variables are most important in their effect on the output variable, the investigator can now examine the effect of variability in an individual input on the output variable while holding other variables as constants. It answers such questions as: how much does the LCC change due to variations in an individual input, e.g., electricity price? What percentage of consumers see a total lower LCC vs. a higher LCC for a given range of electricity prices? This can be done with a sensitivity analysis on selected important variables. The sensitivity analysis determines the changes in model response as a result of changes in individual model parameters through an established quantitative model. It is usually conducted by varying one input parameter, while all other variables are kept as fixed values. The purpose is to show what one-to-one correspondence exists between the output and the input parameter under the study, given an assumption that no other factors play a role. Once knowing the underlying one-to-one relationship between an important input, say the lighting hours, and the output, the LCC saving, we can easily anticipate what likely output variation would be given the variability of the input data. The lighting hours of all commercial buildings in the U.S. reflect the intra-variability (or heterogeneity) in the sampled data set and often is referred as Type A uncertainty [Hoffman and Hammonds, 1994].

3. UNCERTAINTY ANALYSIS

Table 1 illustrates the inputs for the single-value approach to life-cycle cost (LCC) for one class of fluorescent lamp ballasts, the two-lamp F40T12/ES, which is commonly used in the commercial sector. We considered three design options: Design 0 is the baseline, a Magnetic ballast [2] (M). Design 1, the first of the two more efficient designs is the Cathode Cutout (CC). Design 2 is the Electronic Rapid-Start design (ERS). For the range of discount rates in this analysis, (4, 8 and 12 % real), the cathode cutout has the lowest LCC.

We performed the uncertainty analysis on a Macintosh computer, and used the Median Latin Hypercube variation of a Monte Carlo simulation as the sampling method. The data sources for the three key variables are the same as those used in the sensitivity analysis described in detail later in this paper. The electricity prices for all utilities are from investor-owned electric utility sales and revenue data [EIA 1996] for 1995 combined with publicly owned electric utility rates [EIA 1995] for 1994. The annual lighting hours distribution was developed from Xenergy's lighting equipment database [Xenergy, 1995] (see 4.II). We calculated ballast consumer prices by analyzing Bureau of Census reports, using value and shipment data for 1993 and 1995 (see

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[2] For historical reason, the baseline is commonly referred to as "energy efficient" magnetic. It is the least efficient of the three designs considered here, but is more efficient than some other magnetic designs.

4.III). Where data are not as abundant for other inputs, we specified triangular distributions based on prior knowledge.

For many of the variables in this table, the values for each of the three options are the same. The values displaying the important differences among these designs are their ballast retail prices, and the number of fixture watts. More energy efficient ballasts cost more to purchase but require less power to produce a given quantity of light, so they have lower annual electricity costs. The data sources we used to estimate many of these inputs show a wide variability. The U.S. average price of electricity in the commercial sector in the year 2000 is projected to be $0.075/kWh (1994$). Local prices range broadly from $0.01 to 0.15/kWh. Electricity price here represents a Type A uncertainty, because of its wide variability.

There is very little reliable data on ballast lifetime, and thus it represents a Type B uncertainty, because there are an insufficient number of data points. From discussions with facilities managers and other users, we estimate ballast life at 33,000 hours, mean, with a range from 0 to 65,000 hours. Annual lighting hours ranges from 0 to 8,760 hours/yr, with a mean of 3600 hrs/yr. Ballast service life, measured in years, is defined as the ballast life in hours divided by the number of annual lighting hours (hours/yr). The mean is 7.8 years, with a range of 0 to 26 years. The large ranges in these inputs suggest that LCC is highly variable, and it is a variable of Type A.

Figure 1 is the probability density for the total life cycle cost (Tot_lcc) in dollars calculated at 8% discount rate, given the estimated variability or uncertainty in all the input variables. It shows the results of taking 1,000 samples from the possible ranges of the input variables. The total LCC values range from $40 to $465, with a mean of $188. The next step is to attribute to each of the input variables its contribution to this overall uncertainty.

4. IMPORTANCE ASSESSMENT

To determine the ranking of input variables in order of significance of their effect on the uncertainty of the outputs, we conduct an importance analysis on the input variables by calculating the rank order correlation coefficients between each of the input variables and each output variable. Rank order correlation (or Spearman correlation) is measured by computing the ranks of the probability samples, with the largest value assigned a rank of 1 and the smallest, the rank of n, and then computing their correlation. Rank order is a good measure of the strength of monotonic relations regardless of the underlying distributions of the variables involved.

By using the rank order of the samples instead of the actual samples, the measure of correlation is not affected by skewed distributions or extreme values (so-called distribution-free and outlier-resistance measure), and is therefore more robust than the simple correlation (or Pearson correlation).

Importance is then defined as the absolute rank-order correlation coefficient between the sample of output values and the sample for each uncertain input. Unlike commonly used deterministic measures of sensitivity, importance averages over the entire joint probability distribution. Therefore, it works well even for models where the sensitivity to one input depends strongly on the value of another [Lumina Decision Systems, 1996].

Figures 2 and 3 show the relative importance of 9 variables on total life cycle cost (LCC) and change in total life cycle cost (LCC) of the two alternative technologies (Cathode Cutout and Electronic Rapid Start) with respect to Magnetic. For change in LCC (dLCC), the three most important inputs having significant large correlations with the output (greater than 0.4) for all three technologies, are ballast life, electricity price, and annual operating hours. These three inputs will have the dominant effect on change in total life cycle cost.

The same analysis for payback times, as shown in Figure 4, shows that annual operating hours becomes the most influential input, followed by electricity price and ballast consumer price relative to other inputs.

We conclude that the variables that tend to have the most significance in determining the change in LCC (dLCC) and payback times include electricity price, annual operating hours, ballast life, and ballast consumer price. The consistently unimportant variables are times to change lamps and ballasts, labor rates for installing ballasts and lamps, relamp life and lamp price. To address discount rate variability, we ran these calculations for three scenarios: discount rates of 4%, 8% and 12%. This paper reports only results from the 8% scenario.

Having finished a preliminary analysis of the sources of uncertainty, we can now conduct a sensitivity analysis, examining one by one the effect of the key input variables on the output variables. We have also identified key areas for future research: ballast lifetime is an important variable, but data on the lifetime of these commercial ballasts are very poor. A national field study could provide useful information to fill this information gap.

5. SENSITIVITY ANALYSIS

LCC change and payback periods are calculated using a probability distribution curve of possible values for the input variables weighted by their likelihood of occurrence using the Monte Carlo simulation technique. As in the uncertainty analysis, we examined the two-lamp F40T12/ES product class of fluorescent lamp ballasts. We examined four important input variables: electricity price, annual lighting hours, ballast consumer prices and ballast lifetime, which contribute significantly to economic impacts. This analysis shows how variability in these inputs individually affects change in life cycle costs and payback periods.

General Method

Life cycle cost and payback calculations are repeated using a different input value each time for the parameter being varied, while other input parameters are held constant. The calculations are described in an earlier paper, [LBNL 1996]. Each parameter is varied separately, so the interaction between parameters is not considered. The empirical probability distribution of each parameter is estimated from sample data to represent the range of conditions among U.S. consumers. These distributions are weighted so that economic benefits and costs of energy efficiency standards can be assessed on a national scale.

As with the uncertainty analysis, the sensitivity analysis simulations used a Macintosh computer. We constructed the program first using DEMOS, Decision Modeling System, then transferred the program to Analytica [Lumina Decision Systems, 1996]. The software took 1,000 samples from the distribution for one variable at a time, while other variables were kept as single point values taken from the conventional engineering and economic analysis. The Median Latin Hypercube variation of a Monte Carlo simulation was the sampling method. We also tested the

Simple Monte Carlo and Random Latin Hypercube schemes but observed no significant differences in resulting variations. [See Appendix for more information on sampling methods.]

I. Sensitivity to Electricity Price

(a) Data

We have combined data sets from several sources to obtain the commercial sector electricity prices. We used 1995 investor-owned electric utility (IOU) sales and revenue data [EIA 1996] combined with 1994 publicly owned electric utility (POU) rates [EIA 1995]. These sources provide commercial-sector electricity prices from 145 major U.S. investor-owned utilities and 441 publicly-owned utilities. (The 1995 publicly-owned utility data were not available at the time of the analysis.) In 1994, the IOUs accounted for more than 88% of the total electricity sales in the commercial sector.

Figure 5 shows the relative frequency plot (histogram) of electricity prices weighted by sales volume. The x-axis presents the average electricity prices for each utility, ranging from 1.6 to 14.4 ¢/kWh (1995$). The height of the bar represents the probability of the corresponding electricity price, calculated as the ratio of each utility's commercial customer electricity sales to total commercial sales by all the utilities.

Figure 6 and Table 2 show the cumulative probability function (curve) of electricity price to commercial customers constructed from the data in Figure 5. The table or figure can be used to estimate the probability that a given price is less than or equal to any particular value of electricity price. More than 97% of electricity sales in this sector occurs at prices between \$0.04/kWh to \$0.12/kWh, since 2% of sales occur at prices less than \$0.04/kWh, and 0.6% of sales occur at prices greater than or equal to \$0.12/kWh.

(B) Results

Calculating LCC at different values of electricity prices results in Figure 7, which shows a linear relationship between the change in LCC and electricity price. Compared to the Magnetic ballast, the Cathode Cutout and Electronic Rapid Start ballasts reduce LCC (resulting in a negative LCC change) at prices above \$0.032/kWh and \$0.036/kWh respectively. In the case of Cathode Cutout compared to Magnetic, for 99.5% of electricity sales (>\$0.032/kWh), there would be a net savings , and for 0.5%, a net cost to the consumer. Comparing Electronic Rapid Start to Magnetic, for 99% of electricity sales (>\$0.036/kWh), there would be a net savings , and for 1%, a net cost to the consumer.

Two non-linear curves in Figure 8 show the dependence of the payback periods of the Cathode Cutout and Electronic Rapid Start design options relative to Magnetic on the electricity price. Based on the distribution of electricity prices, Table 3 gives the percentage of electricity sales in the U.S. commercial sector by payback period. Payback periods less than or equal to 6 years occur for Cathode Cutout and Electronic Rapid Start for 93% and 95% of electricity sales respectively. Electronic Rapid Start has a shorter payback period than Cathode Cutout at electricity prices below $0.06/kWh, and Cathode Cutout has shorter payback than Electronic Rapid Start at higher electricity prices, Payback relative to Magnetic is less than 6 years for both Cathode Cutout and Electronic Rapid Start at electricity prices above $0.05/kWh. (For reference, the average ballast lifetime is approximately 7.8 years.)

II. Sensitivity to Annual Lighting Hours

(a) Data

The annual lighting hours distribution was developed from Xenergy's XENCAP database [Xenergy 1995]. We received an extract from Xenergy's lighting equipment database, aggregated to the three-digit zip code level. This database contains data from audits of more than 24,000 buildings across the U.S. and has information about operating hours and equipment counts for various lighting equipment types in the buildings audited. We used data from audits performed during 1990 through 1995 to approximate current practice. These data were used to obtain a count of four-foot fluorescent lamp ballasts, of which the two-lamp F40T12/ES ballast is an example, found in each of 21 annual lighting hour "bins" (0 to 8 hrs/wk, >8 to 16 hrs/wk, etc. corresponding to 0 to 416 hrs/yr, 417 to 832 hrs/yr, etc.). This distribution was weighted by building type using data in the 1992 Commercial Building Energy Consumption Survey (CBECS) [EIA 1994]. We then generated values continuously across the 21 lighting hour "bins" through the sampling process so that full variability could be simulated.

Figure 9 illustrates the distribution density curve of lighting hours and Figure 10 shows the corresponding cumulative probability of annual lighting hours. The vertical scale of a density curve does not represent the actual probability of the corresponding x-axis value as it does for a relative frequency plot (histogram) of a discrete distribution. Instead, it depicts "probability density," the probability per x-axis unit of generating a value within a very small range around the x-axis value.

The percentage of ballasts operating in a specific interval of annual lighting hours can be determined easily from the cumulative distribution curve. For instance, the percent of ballasts with annual lighting hours between 2000 and 7000 hours is about 86% (98% operating at less than 7000 hours/year, minus 12% operating at less than 2000 hours/year).

(B) Results

The calculations of LCC were carried out using 1000 simulation samples taken from the specified input distribution for annual lighting hours and mean values for all other parameters. A scatter plot (Figure 11) of the sensitivity analysis of LCC change to lighting hours shows a non-linear relationship between the input and the output, as well as the crossover points at which each curve crosses the zero net savings line (LCC change = 0). The results show that when a magnetic ballast is replaced with a cathode cutout ballast, a net saving in LCC occurs for 98% of ballasts, or those with annual lighting hours above approximately 900 hours/year. A net saving in LCC occurs for 97% of ballasts, or those with operating hours above 1100 hrs/yr when an magnetic ballast is replaced with an electronic rapid start ballast. Combining the sensitivity scatter plot (Figure 11) with the input cumulative probability curve (Figure 10), we can obtain an estimate of the percent of ballasts in the commercial sector having a net LCC savings for each of the design options. In the case of Cathode Cutout compared to Magnetic, for 98% of ballasts there would be a net savings and for 2% of ballasts a net cost. In the case of Electronic Rapid Start compared to Magnetic, for 97% of ballasts there would be a net savings and for 3% of ballasts a net cost.

The proportion of the ballast population with net savings during its life cycle can be represented by the area under the density curve and to the right of the dashed line corresponding to the cutoff point of the lighting hours as illustrated in Figure 12.

We implemented the same procedures for the sensitivity of the payback period to annual lighting hours and the results are presented in Figure 13 and Table 4. At all lighting hours, the Cathode Cutout technology has a slightly shorter payback period than the Electronic Rapid Start technology. For Cathode Cutout ballasts compared to the Magnetic, the payback is less than 6 years for 86% of the ballasts, those operating less than 2000 hours/year. For the Electronic Rapid Start ballast compared to the Magnetic, the payback period is less than 6 years for 84% of the ballasts, those operating for more than about 2300 hrs/yr. These results also show that at a specific number of lighting hours, the Cathode Cutout design has a shorter payback period than the Electronic Rapid Start design.

III. Sensitivity to Ballast Consumer Prices of 2F40T12/ES

(a) Input

We calculated ballast prices by analyzing Bureau of Census reports, using the value and shipments data for 1993 and 1995. A comparison of prices for the two years indicates that the price for Magnetic and Cathode Cutout ballasts (listed as EMAG and CCUT in this source) have increased from 3% to 6%. Although this does not necessarily mean that the same magnitude of increase applies to the end-user price, it does offer an indication of the price trend. Hence, the ballast consumer prices (average or point values) for Magnetic and Cathode Cutout are likely to be on the high side. The high price is estimated as 15% higher than the average price used in the analysis. The low end is estimated 10% lower than the average.

The prices calculated from the Bureau of Census reports for electronic ballasts (Electronic Rapid Start and Electronic Instant Start), on the other hand, decreased by about 15% from 1993 to 1995. Therefore, the consumer prices for electronic ballasts tend to be lower than the average price used in the LCC and payback analysis. The high price is estimated as 5% higher than the average price, and the low price is estimated as 25% lower than the average price.

Based on the estimates, we have specified the distributions of ballast consumer prices for Magnetic (the baseline), Cathode Cutout, and Electronic Rapid Start designs as shown in Table 5. We then produced the distribution of incremental price by subtracting the baseline distribution from the distribution of each design option. These distributions represent variability in the incremental ballast price of each design with respect to the baseline, which causes variability in the LCC change and payback period. We assume that more energy-efficient designs are always more expensive than the baseline. Figures 14 and Table 6 illustrate the two incremental density curves and cumulative distributions respectively for 2F40T12/ES product class.

(b) Results

A scatter plot in Figure 15 showing a linear dependency between LCC change and incremental distribution of ballast consumer price indicates that both Cathode Cutout and Electronic Rapid Start design options will have net savings over the full range of incremental ballast prices. Extending the two straight lines upwards further, the conclusion is that the incremental price of Cathode Cutout-Magnetic would approximately need to exceed \$15 and the Electronic Rapid Start-Magnetic, to exceed \$24, before net costs (increased LCC) would result from these two more efficient designs.

Finally, as shown in Figure 16, a linear relationship is visible between payback period and incremental ballast price. The payback period will increase more rapidly for the Cathode Cutout design than Electronic Rapid Start as their corresponding incremental price goes up. This implies that the time the Cathode Cutout ballasts require for a return on investment may be more sensitive to the change in ballast price than the time required by the Electronic Rapid Start. Table 7 shows payback period given the incremental ballast price of each design option.

IV. Sensitivity to Ballast Lifetime

(a) Input

The lifetime of ballasts has been estimated as a triangular distribution (Figure 17) specified by three parameters. They are: minimum lifetime, 2,000 hours; mode, 45,000; maximum lifetime, 80,000. The mode is the lifetime that has the greatest probability density (or the highest possibility). Estimates of the three parameters are based on engineering judgment from the limited data available[3].

Since the distribution is asymmetric, with a larger range to the left, the mean (42,330) is less than the mode (45,000). Figure 18 and Table 8 show the cumulative probability of the lifetime of the ballasts having specific values. Ballasts having lifetimes less than 20,000 hours constitute 10%; 20,000 to 60,000 hours are 75% of all ballasts; and the remaining 15% have lifetimes greater than 60,000 hours.

3 Because the probability density at two ends is low, the minimum and maximum values were not picked up by the sampling process as shown in the statistics table in Figure 17.

(a) Results

Two non-linear curves in Figure 19 present the change in LCC over the range of ballast lifetime. They were generated from a simulation run of 1,000 samples. At low ballast lifetimes, Electronic Rapid Start has higher net costs than Cathode Cutout. Because Cathode Cutout has a different relamp period from that of the Magnetic and Electronic Rapid Start ballasts (16,150 versus 19,000 hours), the LCC change curve (Cathode Cutout-Magnetic) is discontinuous.

Note that there are four discontinuous segments in the LCC change (Cathode Cutout-Magnetic) curve caused by the difference in relamp periods between the Cathode Cutout and the baseline Magnetic. The four segments' ranges in lighting hours are 16,150 to 19,000; 32,300 to 38,000; 48450 to 57,000; and 64,600 to 76,000. The first two segments result in net costs (a positive LCC change) and the last two, in net savings (negative LCC change). By examining both Figure 18 and 19, we made an approximation that for 82% of Cathode Cutout ballasts, there would be a net saving relative to Magnetic and for 18%, a net cost. We estimated the total net savings (83%) and net costs (17%) for Electronic Rapid Start taking into account both the primary trajectory and the segments.

To see the percentile of ballasts in different LCC change intervals, we have produced the cumulative probability curve of LCC change (Figure 20) and a bar chart (Figure 21). Most of the Cathode Cutout ballasts, about 70%, have moderate net savings, \$0 to \$10, during their life cycles. A majority of the Electronic Rapid Starts, about 60%, generally have higher net savings, ranging from \$5 to \$15.

6. REFINED DISTRIBUTIONS AND RESULTS

The significance of the importance assessment is that it allows analysts to identify the input variables that have more impacts on the output than the others in a quantitative model. After knowing which variables are more important, they can focus time and effort on collecting more accurate information or formulating better distribution functions to reduce uncertainty in these influential variables so that the simulation result would have less variation. Therefore refining analysis with revised distributions for the important variables becomes a necessary step for a complete uncertainty study. In this section, we present revised distributions for three variables identified in Section 4 (The Importance Assessment) and a brief description for each.

I. Distributions

Ballast Price

A refined distribution of the incremental ballast price was obtained by performing a nation-wide survey of ballast prices in the market place. With the goal of gathering ballast price data, LBNL attempted to contact two electrical distributors per state in late 1998 and January 1999. Each distributor was asked to give a contractor price for each of the ballasts, assuming an order for 100 of any given ballasts, for a “good” client. The resulting prices were then marked-up by 13% to account for contractor mark-up. This is the mark-up a lighting contractor would charge its client for buying and installing the ballasts. Table 9 shows two normal distribution parameters of the incremental ballast prices for both Cathode Cutout and Electronic Rapid Start.

Table 9 Mean and Standard Deviation of Incremental Ballast Prices

Incremental Ballast Price (1997$) - Normal Distribution

Design Options (2-Lamp Feature)	Mean Value	Standard Deviation
Cathode Cutout	9.04	1.36
Electronic rapid Start	11.4	1.71

Electricity Price

The electricity price distribution was further refined so as to use the electricity price at the margin that a consumer faces as a result of a decrease in electricity consumption. Marginal electricity prices in $1997/kWh are used. A detailed explanation of the process for deriving these marginal electricity rates can be found in the Technical Support Document (TSD) [US DOE, 2000]. Electricity prices projected for the year 2003 are used because that is the earliest year in which changes to the minimum ballast efficiency standards could occur.

Electricity price is a function of the average price distribution obtained from the Energy Information Agency's data on revenue and sales, for the industrial and commercial sectors by utility, and the epsilons discussed in the TSD. Epsilon is the percent difference between the average electricity price and the marginal price calculated for each customer on each tariff (the average epsilon is 5.5%). Using the epsilons discussed in the TSD, the marginal electricity price is calculated as:

Marginal Electricity Price = Sales Weighted Average Price x (1 + Epsilon)

Figure 22(A) and (B) illustrate the distributions of 1997 commercial average electricity price and Epsilons that are used to calculate the marginal electricity rate.

Ballast Life

An average life of 50,000 hours is assumed for the ballast with a Weibull distribution starting at 18,000 hour life used to describe the uncertainty in the lifetime as shown in Figure 23. Weibull distributions describe data resulting from life and fatigue tests and are commonly used to describe failure time in reliability studies.

Annual Operating Hours

There is no further refinement on this variable.

II. Simulation Results

With the revised distributions discussed above, we conducted a simulation with 10,000 trials using an Excel spreadsheet model and Crystal Ball, a commercial simulation software. Figures 24 - 25 present estimated distributions of LCC savings, changes in life-cycle cost of a design option from the baseline, for both Cathode Cutout and Electronic Rapid Start (US DOE, 2000). It is shown that with the 10,000 samples used, the average cost for CC is about $2 and the average saving for ERS is $6, respectively. The figures have also revealed that more than 30% or 80% of the samples would have saved money if CC or ERS had been adopted.

Payback distributions for CC and ERS are illustrated in Figures 26 and 27. They show that for the 10,000 cases analyzed for each lamp/ballast combinations, there are more than 70% or 95% of samples whose payback period is less than 15 years for CC or ERS respectively (US DOE, 2000).

Finally, an importance assessment is revisited with the three revised distributions (Ballast price, Electricity price, and Ballast life-time). With comparisons with Figures 2 and 3, the results, Figures 28 and 29, show that the refinement of distributions do not alter the relative rankings of those important variables identified before for both LCC changes and payback calculations. The only exception is that the ballast lifetime with a new Weibull distribution depicted in Figure 23, appears less influential in determining the LCC changes than with the previous Triangular distribution shown in Figure 17.

7. GENERAL CONCLUSIONS

We have applied uncertainty determination, importance assessment, and sensitivity analyses to study the variability of life cycle cost and payback times for two-lamp electronic ballasts typically found in the commercial sector. The overall uncertainty determination illustrates the entire spectrum of possible output values associated with their likelihood of occurrence in response to the various values of the inputs. The importance assessment shows that for the LCC calculation out of nine variables, with distributions representing variations of values, electricity price, ballast life, and annual lighting hour have the most impact on the variation in the output of total life cycle cost, and that out of eight variables, annual lighting hours, electricity price, and ballast consumer price are more important than others in determining the uncertainty in the payback time for two energy-efficient alternatives to the current magnetic ballast. These results identify the input variables with the most significant contribution to uncertainty. These variables are therefore singled out for sensitivity analysis.

Using sensitivity analysis, we have shown the effect of each of four variables, electricity price, annual lighting hours, ballast price, and ballast life, on total life cycle cost and payback time to each of two energy-efficient alternatives, Cathode Cutout and Electronic Rapid Start, with respect to the magnetic ballast. The results can be stated in the form of a comparison of ranges of input and output variables. For example, for electricity prices > \$0.032/kWh, the sensitivity analysis shows that for 99.5% of electricity sales there would be a net savings for Cathode Cutout compared to Magnetic, while for 99% of electricity sales, there would be a net savings for Electronic Rapid Start compared to Magnetic.

We have demonstrated that importance assessment and sensitivity analyses offer valuable tools for analysts and policy makers who are assessing proposed energy efficiency standards that require the adoption of new technologies. Uncertainty analysis allows the investigator to determine which of the values are contributing the most to uncertainty in the output variables, e.g. life cycle cost or payback times, and which are not affecting these outputs substantially. Thus, the investigator can focus more resources on gathering the most extensive and accurate data for only the most important input variables, and spend less effort on the less important variables.

Sensitivity analysis provides comparisons of the benefit or cost to consumers of new and baseline technologies for a given range of values of a single variable such as electricity price or product cost. The analysis can provide an indication of how many consumers will benefit from the adoption of the technology, and how many will incur a cost at a given range of the input variable. This information helps reduce the number of scenarios that a policymaker must evaluate from the thousands, involving a dozen variables or more, to just a handful, involving a few key variables.

Finally, a simulation run of the LCC and payback is conducted with all 9 distributions, including four revised distributions. Although the average values of output do not show significant difference from the result using the previous distributions, the variations of LCC change, the difference between the design options and the baseline, are reduced significantly.

8. APPENDICES

A. Monte Carlo Simulation

Simulation can be defined as the repetitive analysis of a mathematical model. The Monte Carlo simulation refers to a class of simulation techniques for decision-making in which probability distributions are used to obtain input parameters when the model is being evaluated (Ripley, 1987; Smith, 1994; Burmaster and Anderson, 1994). The distributions are used to generate random outcomes for each parameter that is considered to be important and has a probabilistic value.

A distribution can either be approximated by a theoretical one such as a normal or exponential distribution curve, or represented by an empirical probability table in which the probability of occurrence of various distinct values (levels) are estimated by their relative frequencies in sampled data or weighting factors from the existing data sources. These random outcomes are then used in calculations of the decision criterion (or measure of merit), which in this analysis are life cycle cost and payback times. Since other parameters are entered as fixed values in all calculations, the variability in the outputs (LCC and Payback) calculated by Monte Carlo simulation is due entirely to the model uncertainty and the variation in the parameters under study.

The core of the Monte Carlo simulation is that the outcomes of the parameter under study must be randomly selected from the distribution representing it. Two sampling methods widely used in computer simulations are the Simple Monte Carlo and the Latin Hypercube (Morgan and Henrion, 1990). The Simple Monte Carlo sampling first draws a cumulative probability curve from a specified distribution (theoretical distribution or empirical probability table). Then a random generator is used to produce a set of independent, uniformly distributed numbers, R_n, (i.e., numbers between 0 and 1). Through the rule of an inversion (Ripley, 1987), a set of the input values X_n corresponding to the cumulative probability curve can be obtained for a given sample size *n*.

However, in a parametric sensitivity study, the ultimate goal of the simulation is not the randomness but the resulting equidistribution (or equiprobable) properties of the sets of values in the parameter space (Morgan and Henrion, 1990). To achieve this, a technique called Latin Hypercube Sampling (LHS) that uses a stratified sampling approach, was originated (Iman and Conover, 1980). It divides each input distribution into *n* (sample size) equiprobable intervals. A single value is taken at random from within each of these intervals, based upon the probability distribution. This produces a sample of n values for each input distribution which are more uniformly spread out than for strict random sampling. In a variation of LHS, Median Latin Hypercube, the median of each of the *n* intervals is chosen instead of a random value so that a more uniform sampling is produced.

B. Calculations Used in the Analysis (Two Lamp F40T12/ES)

(1) General Inputs

(B1.1)

$$Bservice = \begin{cases} \frac{Blife}{Ophr\_lt}, Ophr\_lt > 0 \\ 0, otherwise \end{cases}$$

(B1.2)

$$Lprice = \begin{cases} (.95xLLPx.6 + .05xLDP)xBNNxDEF, LDP > 0 \\ (.95xLLPx.6 + .05xLLPx.45)xBNNxDEF, otherwise \end{cases}$$

where:

LDP = 1.18 ($/lamp) DGSC lamp list price (1994$);

BNN = 2, number of lamps per ballast;

DEF = 1, deflator factor.

(B1.3)

$$Period = \frac{Blife}{Ophr\_lt}$$

(B1.4) $$Pwf = \frac{1}{Drate} x \left[1 - (1 + Drate)^{-Period} \right]$$

where: *Drate* = {0.04, 0.08, 0.12}, discount rate chosen;

Table B1. Parameters in General Inputs

Parameter	***Definition***	***Forms of Uncertainty***	***Source***
Blife	Lifetime of ballast (hrs)	Triangular (2K, 45K, 80K)	Prior knowledge
Bservice	Ballast lifetime in service (yrs)	Derived	Calculated in (B1.1)
Ele_pri	Electricity price ($/kWh)	Empirical Distribution	EIA 1995 & 1996
Labor1	Helper's Labor rate for installing lamp ($/hr)	Triangular (18.75, 29.35, 34.38)	Subjective Judgement
Labor2	Electrician's labor rate for installing ballast ($/hr)	Triangular (35, 42.10, 52.5)	Subjective judgement
Lprice	Lamp equipment cost ($)	Triangular (1.68, 2.77, 5.97	Prior knowledge
Ophr_It	Annual Lighting hours (hrs/yr)	Empirical Distribution	Xenergy 1995
Period	Period of analysis (yrs)	Derived	Calculated in (B1.3)
Pwf	Present worth factor	Derived	Calculated in (B1.4)
Llp	Lamp list price ($)	Triangular 1.68, 2.77, 5.97)	Prior knowledge

(2) Total Installed Cost

Total installed cost of a ballast is the sum of costs for ballast and lamps. Equation (B2.1) calculates the present value of the quantity:

(B2.1) $$Pv\_lampbal_i = Pv\_lamp + Pv\_bal_i$$

where: I = 0, 1, 2; an index for design options.

Each of the two components is computed from a set of equations shown in the following:

I. Lamp Installed Cost:

The lamp installed cost refers to the costs of installing all replacement lamps during the ballast life time; whereas the cost of installing the initial lamp(s) are included in the calculation of ballast installed cost.

(B2.2) $$Cost\_llab = \left(\frac{Ttc\_lam}{60}\right) x\ Labor1$$

(B2.3) $$Lservice = \begin{cases} \frac{Relamp}{Ophr\_It}, Ophr\_It > 0 \\ 0, otherwise \end{cases}$$

(B2.4) $$Per1 = Round\left[\left(\frac{Bservice}{Lservice}\right) + 0.5\right] x\ Lservice$$

(B2.5)
$$Pv\_lamp = \left[\frac{(Cost\_llab + Lprice) xDrate}{1-(1+Drate)^{Lservice}}\right] x \left[\frac{1-(1+Drate)^{-Per1}}{Drate}\right] - (Cost\_llab + Lprice)$$

Table B2 lists all parameters used in the calculation of the lamp installed cost and briefly describes the forms of their uncertainties and sources.

Table B2. Parameters in Lamp Installed Costs

Parameter	***Meaning***	***Forms of Uncertainty***	***Source***
Cost_llab	Lamp labor cost ($)	Derived	Calculated in (B2.2)
Lservice	Lamp service life (yrs)	Derived	Calculated in (B2.3)
Per 1	Intermediate variable * (yrs)	Derived	Calculated in (B2.4)
Pv_lamp	Present value of lamp cost ($)	Derived	Calculated in (B2.5)
Ttc_lam	Time to change lamp (min.)	Triangular (18.8,23.5,28.2)	Prior knowledge

* used to allow calculation of the full cost of the final replacement lamp.

II. Ballast Installed Cost:

Likewise, ballast installed cost is computed from the following set of equations. Table B3 gives a summary of the parameters in the calculations.

(B2.6) $$Cost\_blab = \left(\frac{Ttc\_bal}{60}\right) x \left(\frac{Labor1 + Labor2}{2}\right)$$

(B2.7) $$Bprice_i = Bconpri_i + Lprice$$

(B2.8) $$Pv\_bal_i = \left[\frac{(Cost\_blab + Bprice_i)}{1-(1+Drate)^{-Bservice}}\right] x \left[\frac{1-(1+Drate)^{-Period}}{Drate}\right]$$

where: $i = 0, 1, 2;$ representing design options

As mentioned above, the ballast is installed with lamp(s) and therefore the ballast labor cost, *Cost_blab*, as well as the present value of ballast installed cost, Pv_bal_i, have included these initial lamp(s) costs.

Table B3. Parameters of Ballast Installed Cost

Parameter	***Meaning***	***Forms of Uncertainty***	***Source***
Bconpri0	Baseline ballast consumer price ($)	Normal (11.20,12.44,14.31)	Subjective judgement (*)
Bconpri1	Design 1 ballast consumer price ($)	Normal (16.97,18.86,21.69)	Same as above
Bconpri2	Design 2 ballast consumer price ($)	Normal (21.71,28.94,30.39)	Same as above
$Bprice_i$	Ballast price ($)	Derived	Calculated in (B2.7)
Cost_blab	Ballast labor cost ($)	Derived	Calculated in (B2.6)
Pv_bal_i	Present value of ballast cost ($)	Derived	Calculated in (B2.8)
Ttc_bal	Time to change ballast (min.)	Triangular (24,30,36)	Prior knowledge

*The judgement is based on manufacturer's retail price and 20% of it is taken as the standard deviation

(3) <u>Annual Electricity Cost</u>

This part of analysis is to calculate annual electricity cost during the entire lifetime of a ballast. Since each engineering design has different energy efficiency, electricity usage varies. Energy saving is then contributing to the life-cycle cost and is one of the criteria in engineering design. The equations are shown below.

(B3.1) $$Elec\_use_i = \frac{Nwatt_i\, x Ophr\_It}{1000}$$

where: $Nwatt_0$ = 72.7 (W), normalized fixture watt for the baseline (Magnetic);

$Nwatt_1$= 65.6 (W), normalized fixture watt for design option 1 (Cathode Cutout);

$Nwatt_2$ = 61.9 (W), normalized fixture watt for design option 2 (Electronic Rapid Start);

(B3.2) $$Elec\_cost_i = Elec\_use_i \; x \; Ele\_pri$$

where: $i = 0, 1, 2;$ representing design options

Table B4. Parameters of Electricity Cost

Parameter	***Meaning***	***Forms of Uncertainty***	***Source***
$Elec\_cost_i$	Annual electricity cost, ($)	Derived	Calculated in (B3.2)
$Elec\_use_i$	Annual electricity use, (kWh/yr)	Derived	Calculated in (B3.1)

(4) <u>Life Cycle Cost and Payback</u>

The final part of the analysis is to compute total and annual life-cycle cost as well as payback period for each engineering design of the product. The equations are the following:

(B4.1) $$Tot\_lcc_i = Pv\_lampbal_i + Elec\_cost_i \; x \; Pwf$$

(B4.2) $$Ann\_lcc_i = \frac{Tot\_lcc_i}{Pwf}$$

(B4.3) $Bal\_cost_i = Bprice_i + Cost\_blab$

(B4.4) $$Anlmp\_cost_i = \frac{Ophr\_ltx(Lprice + Cost\_llab)}{Relamp}$$

(B4.5) $$Payback_i = \frac{Bal\_cost_i - Bal\_cost_0}{\left(Elec\_cost_0 - Elec\_cost_J\right) + \left(Anlmp\_cost_0 - Anlmp\_cost_i\right)}$$

where: i = 1, 2; representing design options other than the baseline.

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Table 1. Life-Cycle Costs of Fluorescent Lamp Ballasts, Two Lamp F40T12/ES, Commercial Sector

Technology Option	Ballast Retail Price ($1994)	Ballast Equip + Labor Cost at 8% discount ($1994)	Total Installed Cost ($1994)	Fixture Watts (Normal)	Annual Energy Use (kWh/yr)	Annual Electricity Cost ($1994)	Total LCC ($1994) at Real Discount Rates 4%	8%	12%
Magnetic (M)	12.44	33.57	44.03	72.7	308	23.06	198	174	155
Cathode Cutout (CC)	18.86	39.99	50.45	65.6	278	20.82	190	168	151
Electronic, Rapid Start (ERS)	28.94	50.07	60.53	61.9	262	19.65	192	171	155

Common Values of the Parameters Used in the LCC of the Three Options

Cost Parameters	
2000 Electricity Cost ($1994/kWh)	$0.075
Labor Rates, helper/electrician ($1994)	$29.35/$42.10
Lamp Retail Price ($1994)	$3.28
Lamp Labor Cost ($1994)	$11.50
Ballast Labor Cost ($1994)	$17.86
PV Lamp Equip + Labor Cost ($1994 at 8%)	$10.45

Time Parameters	
Annual Lighting Hours (hours)	4230
Period (years)	7.80
Service Life (years)	4.49
Lamp Time to Change (minutes)	23.5
Ballast Time to Change (minutes)	30
Ballast Service Life (years)	7.8
Relamp Life (hours)	19000

Figure 1. Probability Density of the Total LCC ($) of the Baseline (Magnetic)
(Two Lamp F40T12/ES)

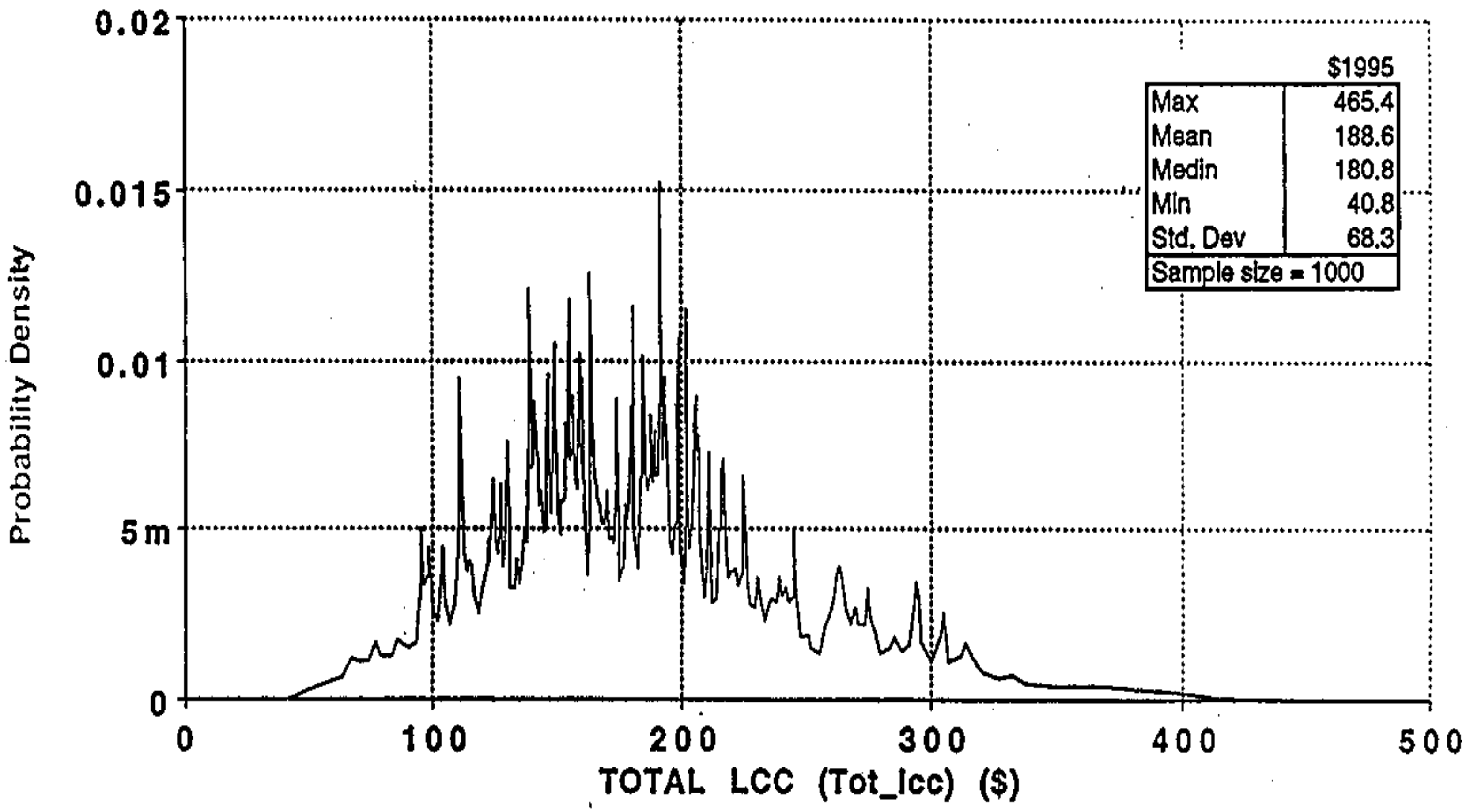


Figure 2. Relative Importance of the Inputs to Total LCCs

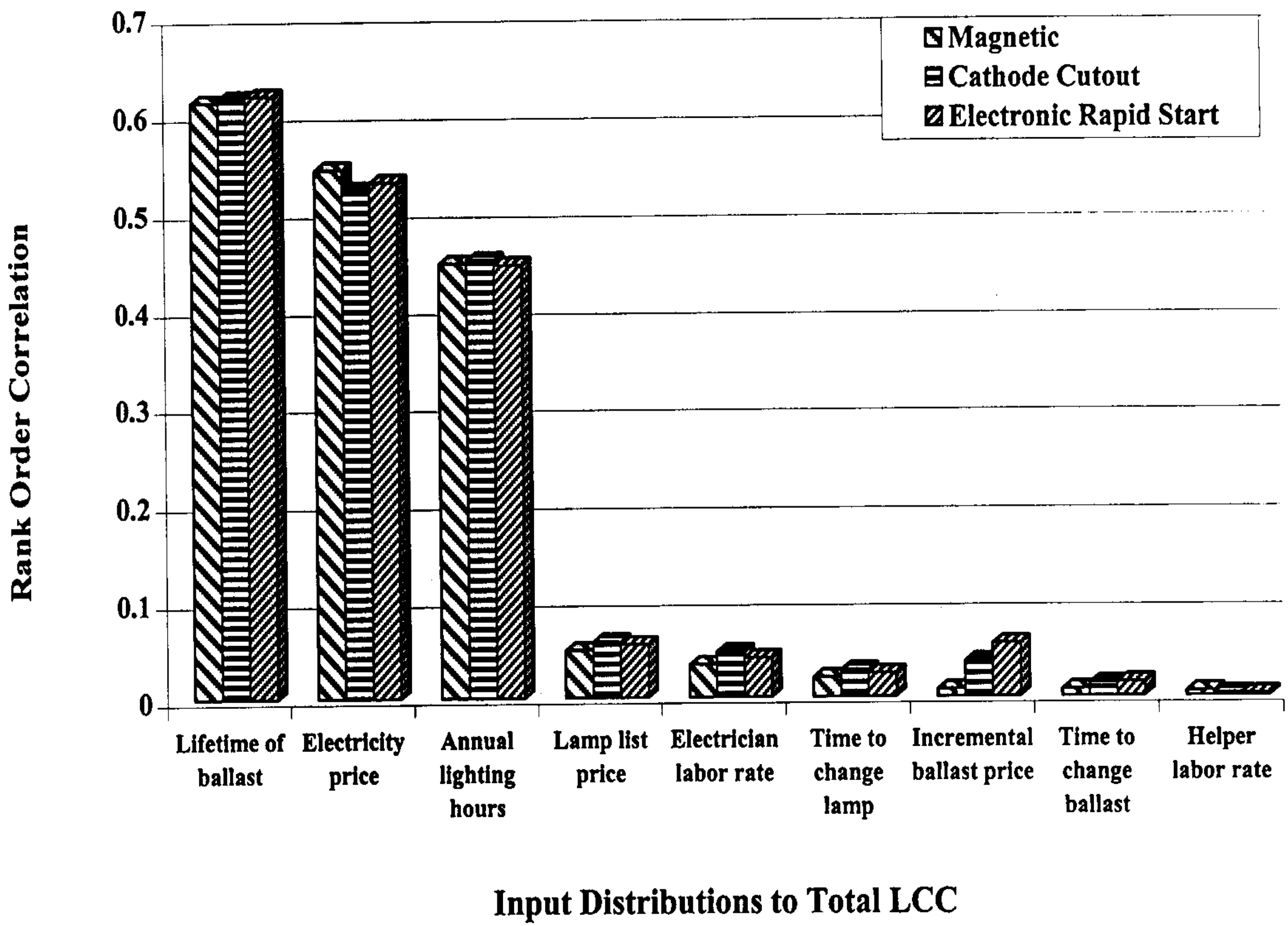


Figure 3. Relative Importance of the Inputs to Total LCC Changes

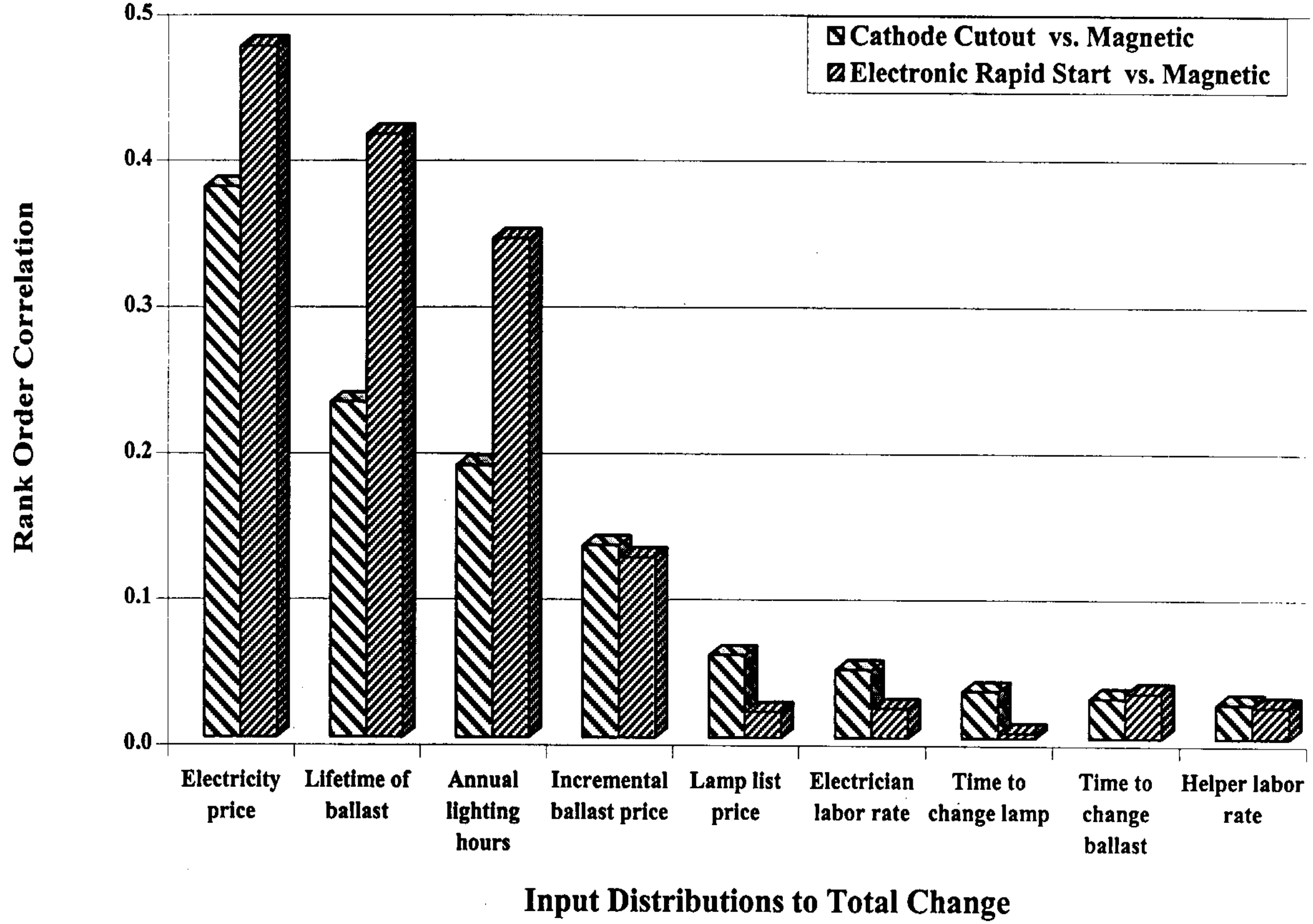


Figure 4. Relative Importance of the Inputs to Paybacks

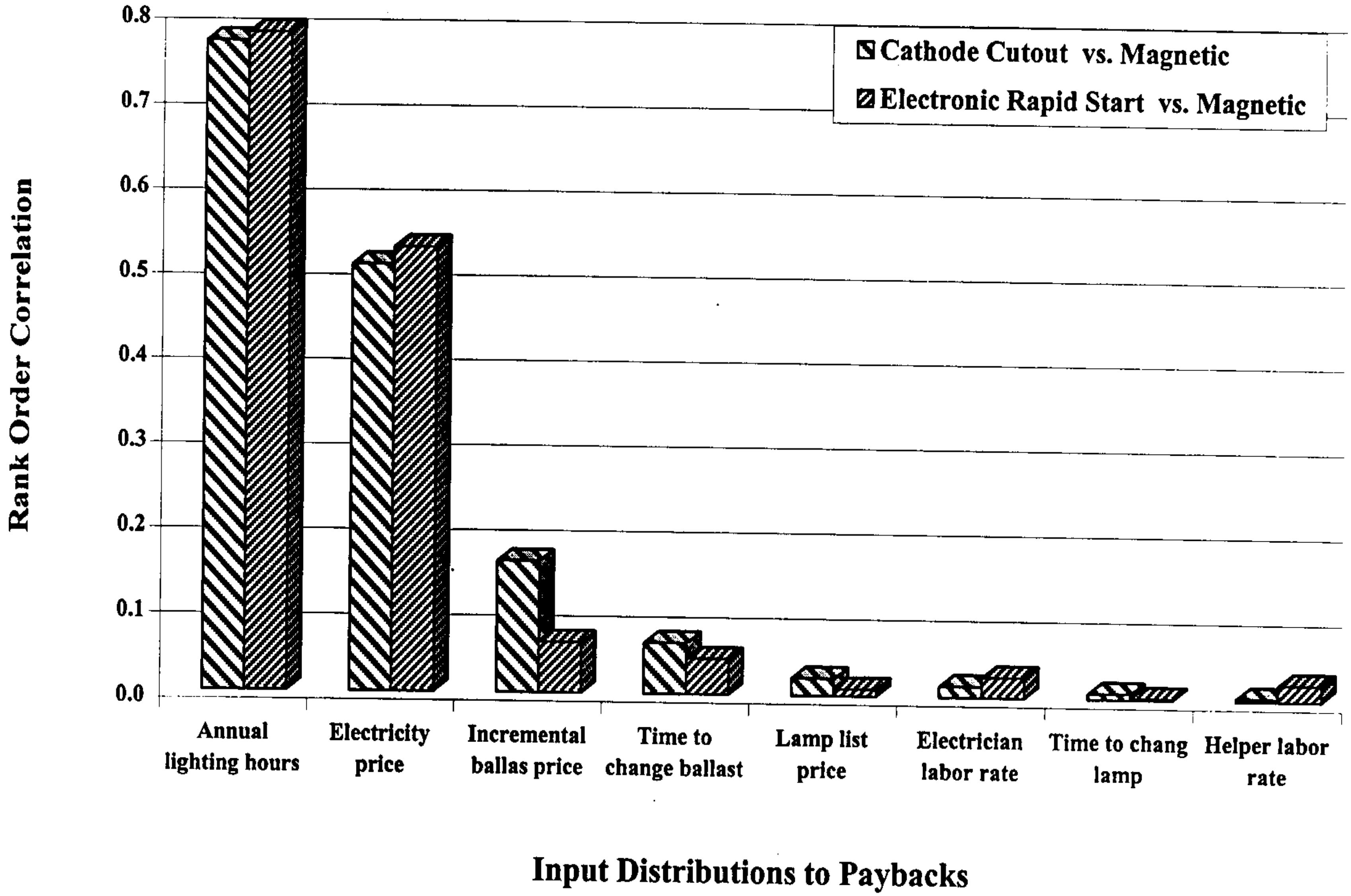


Figure 5. U.S. Commercial Sector Electricity Price ($1995/kWh)

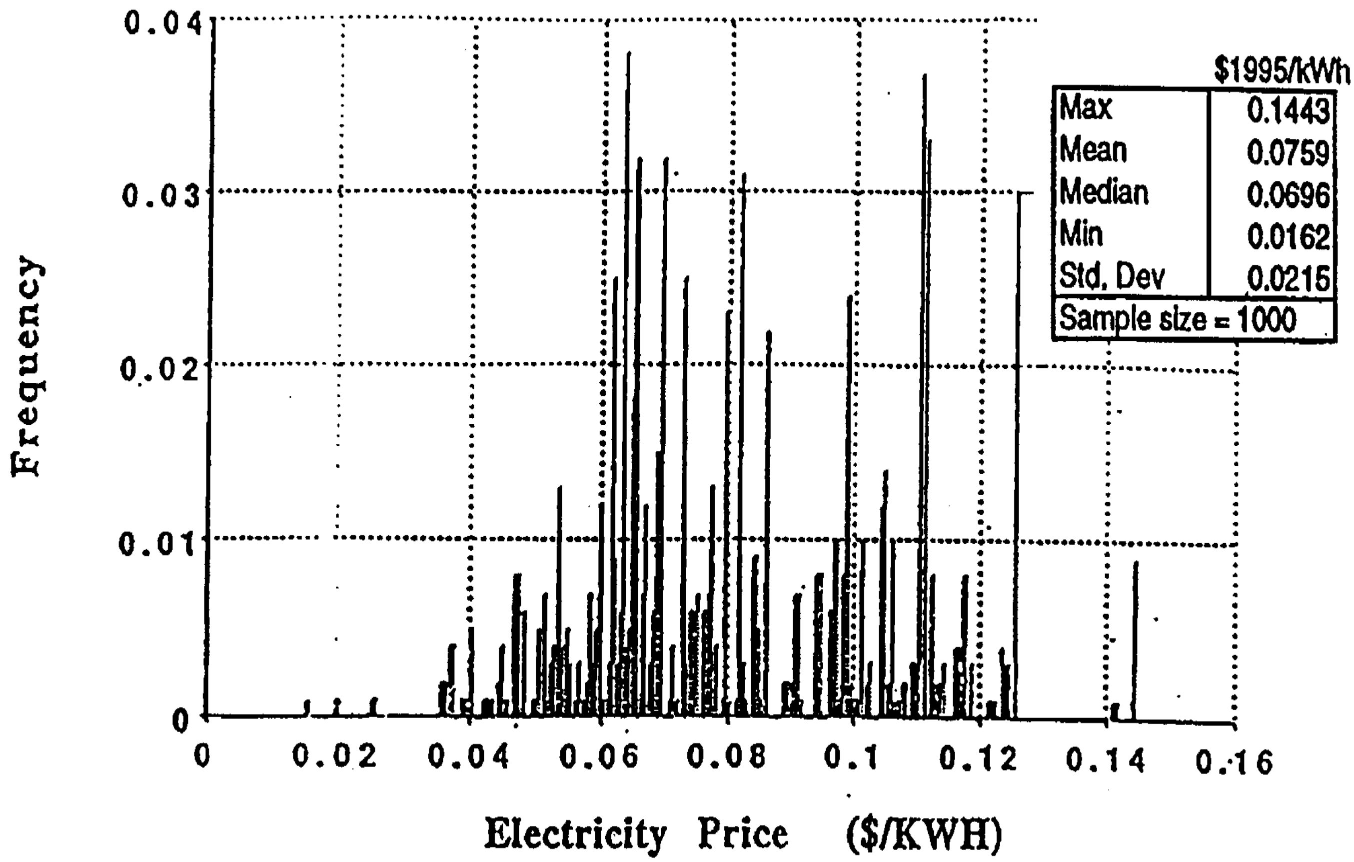


Figure 6. Cumulative Probability of Commercial Electricity Price in 1994 - 95

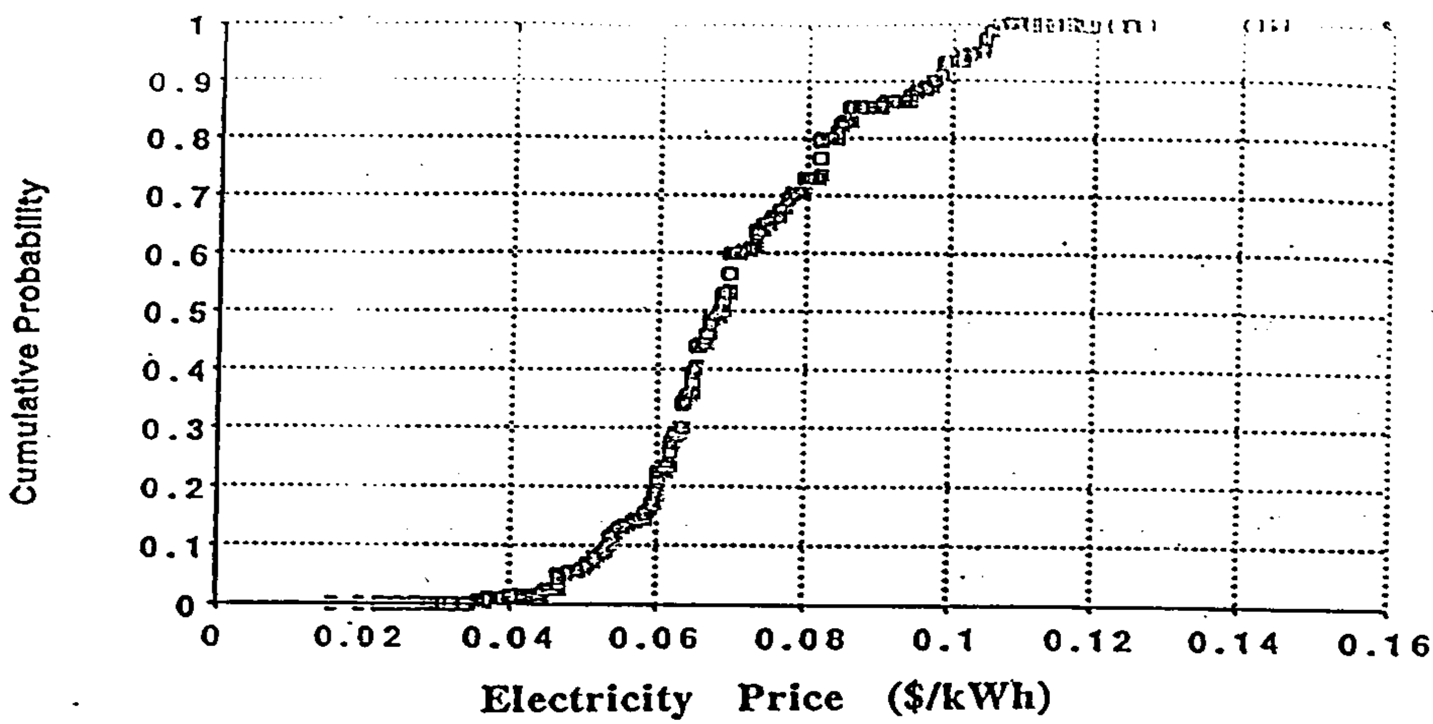
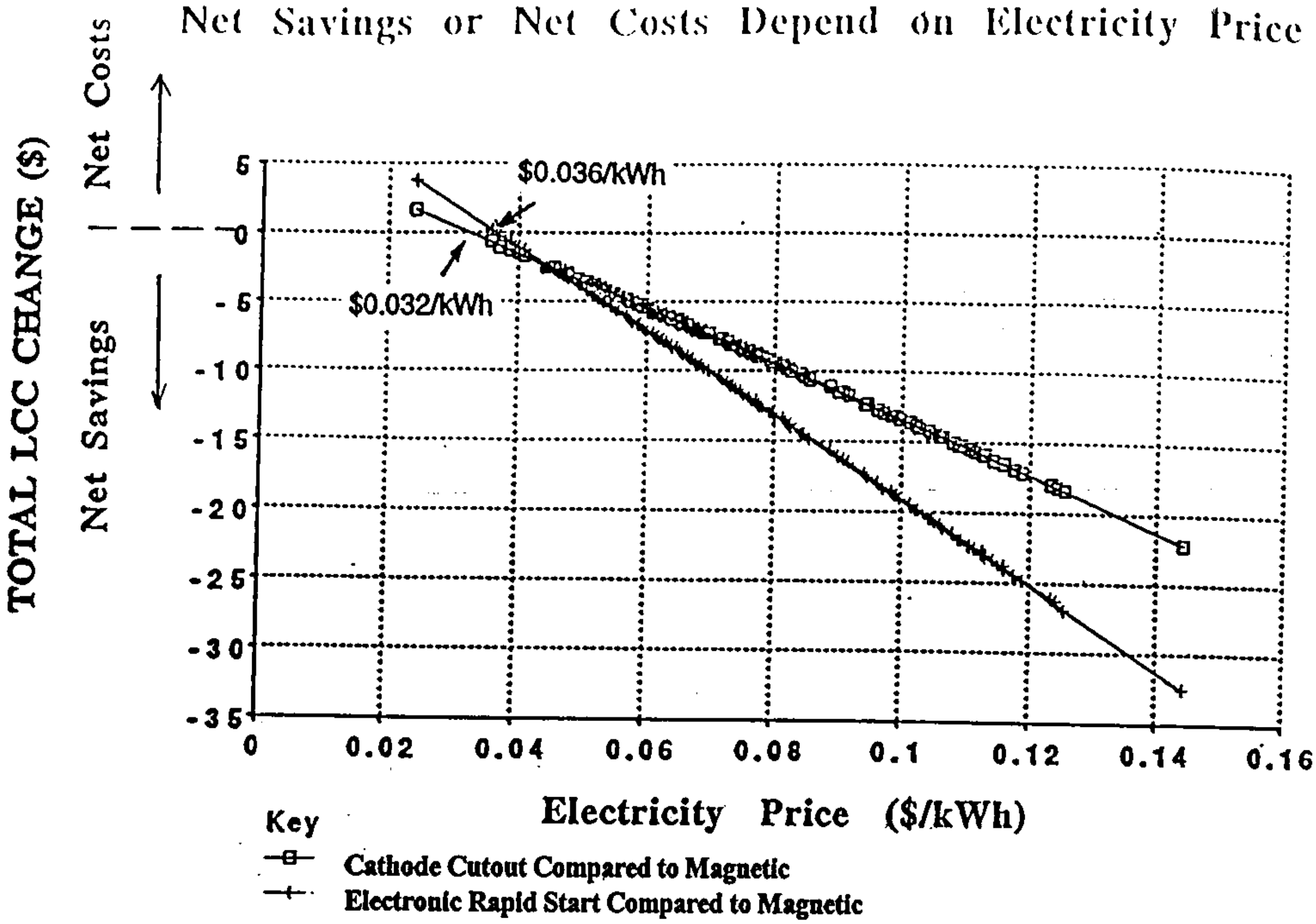


Table 2. Cumulative Probability of Commercial Electricity Price

Price less than ($/kWh)	Percent of sales
0.02	0.1%
0.04	2.0%
0.06	21.0%
0.08	73.0%
0.10	94.0%
0.12	99.4%
0.14	99.6%
0.16	100.0%

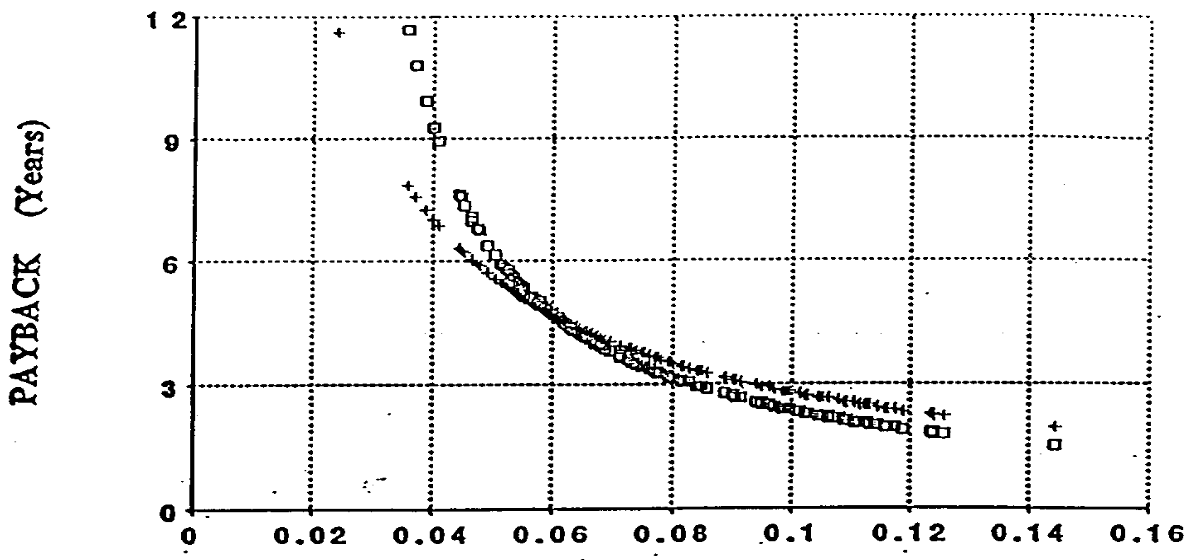
Figure 7. TOTAL LCC CHANGE ($): Two Lamp F40T12/ES

Net Savings or Net Costs Depend on Electricity Price



For CC-EEM, Net Savings Occur Above $0.032/kWh for 99.5% of Electricity Sales
For ERS-EEM, Net Savings Occur Above $0.036/kWh for 99% of Electricity Sales

Figure 8. Sensitivity of PAYBACK To Electricity Price
Two Lamp F40T12/ES



Key
□ Cathode Cutout Compared to Magnetic
+ Electronic Rapid Start Compared to Magnetic

Table 3. Payback by Percent of U.S. Commercial Electricity Sales
(Two Lamp F40T12/ES)

Payback Less Than (Years)	Cathode Cutout vs. Magnetic	Electronic Rapid Start vs. Magnetic
3	20%	14%
6	93%	95%
9	98%	99%
12	99.5%	99.5%

Figure 9. Ballast Annual Lighting Hours in U.S. Commercial Stock (Four Foot Lamp)

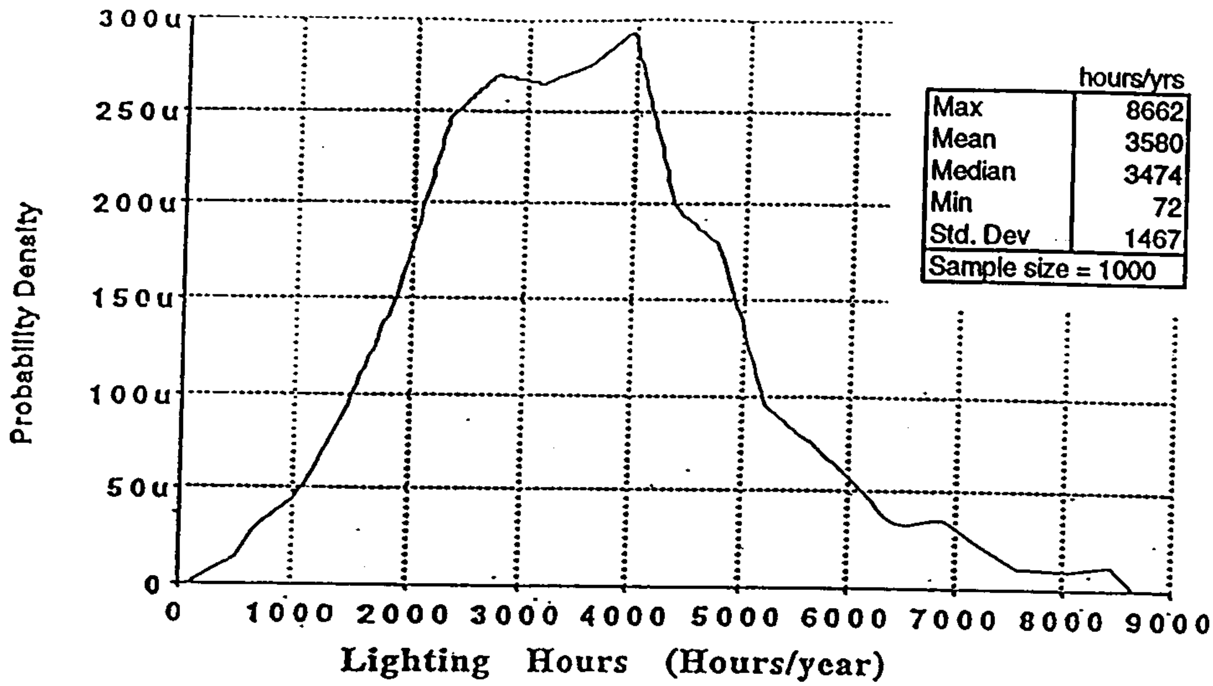
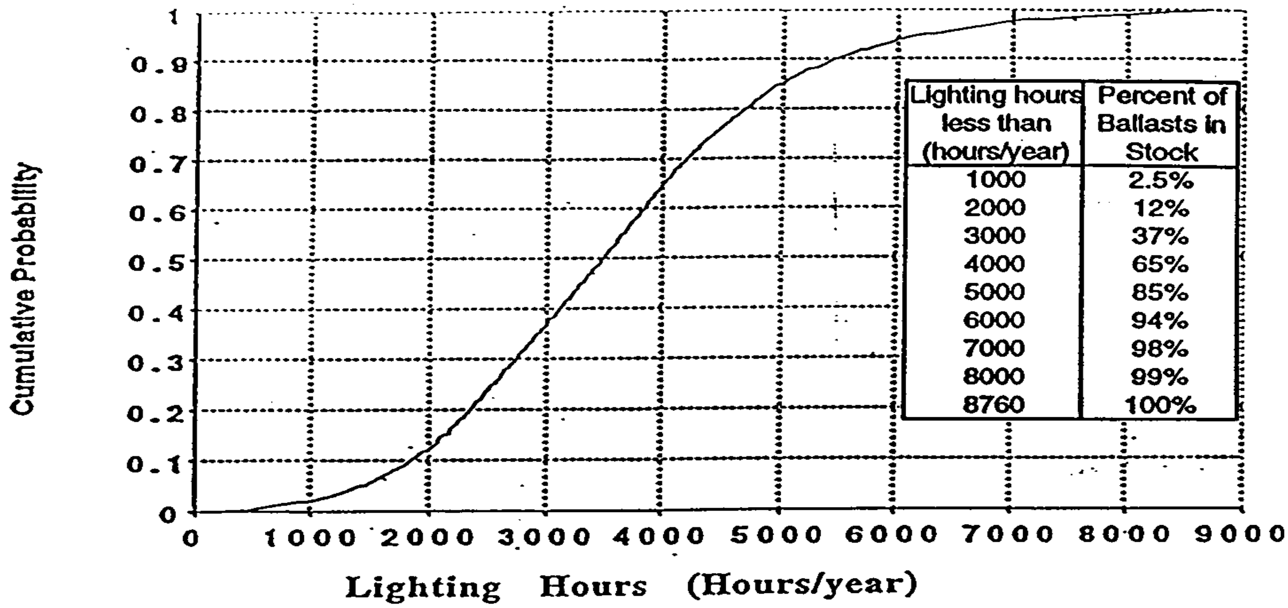


Figure 10. **Cumulative Probability of Annual Lighting Hours (Four Foot Lamp)**



Lighting hours less than (hours/year)	Percent of Ballasts in Stock
1000	2.5%
2000	12%
3000	37%
4000	65%
5000	85%
6000	94%
7000	98%
8000	99%
8760	100%

Figure 11. TOTAL LCC CHANGE ($): Two Lamp F40T12/ES
Net Saving or Net Cost Depend on Lighting Hours

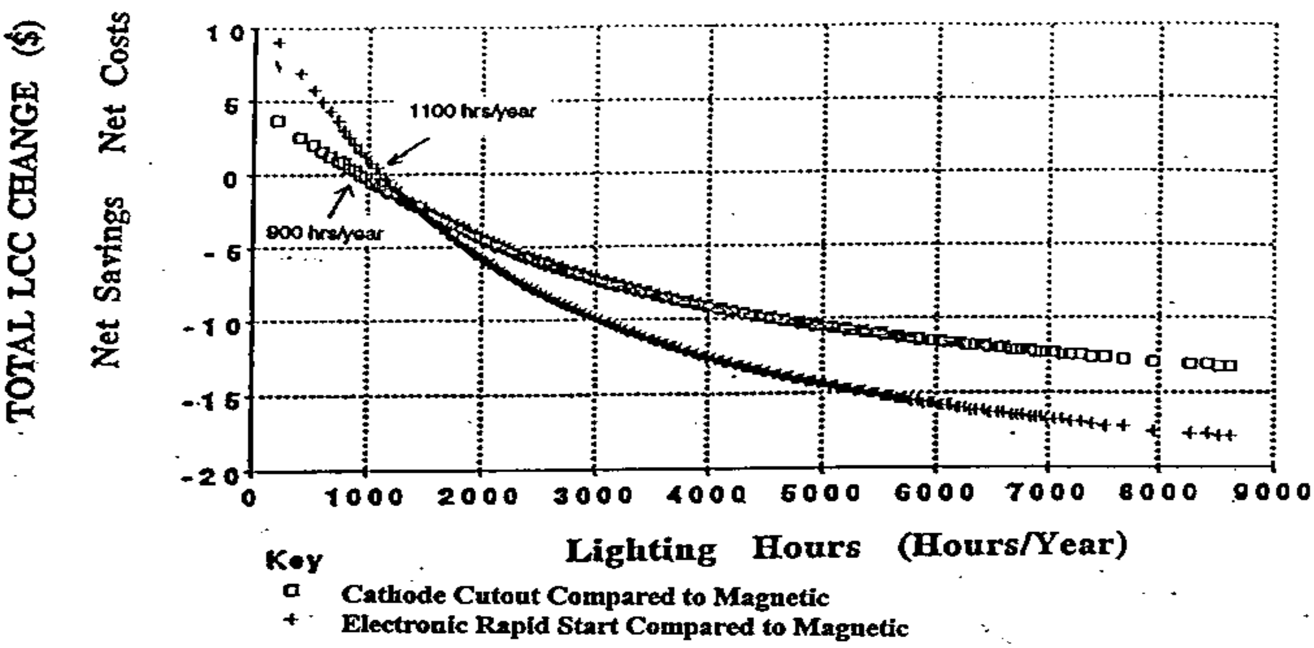


Figure 12. Net Savings Occur above 900 hours/year with 98% of Ballasts and 1100 hours/year 97% for CC and ERS respectively

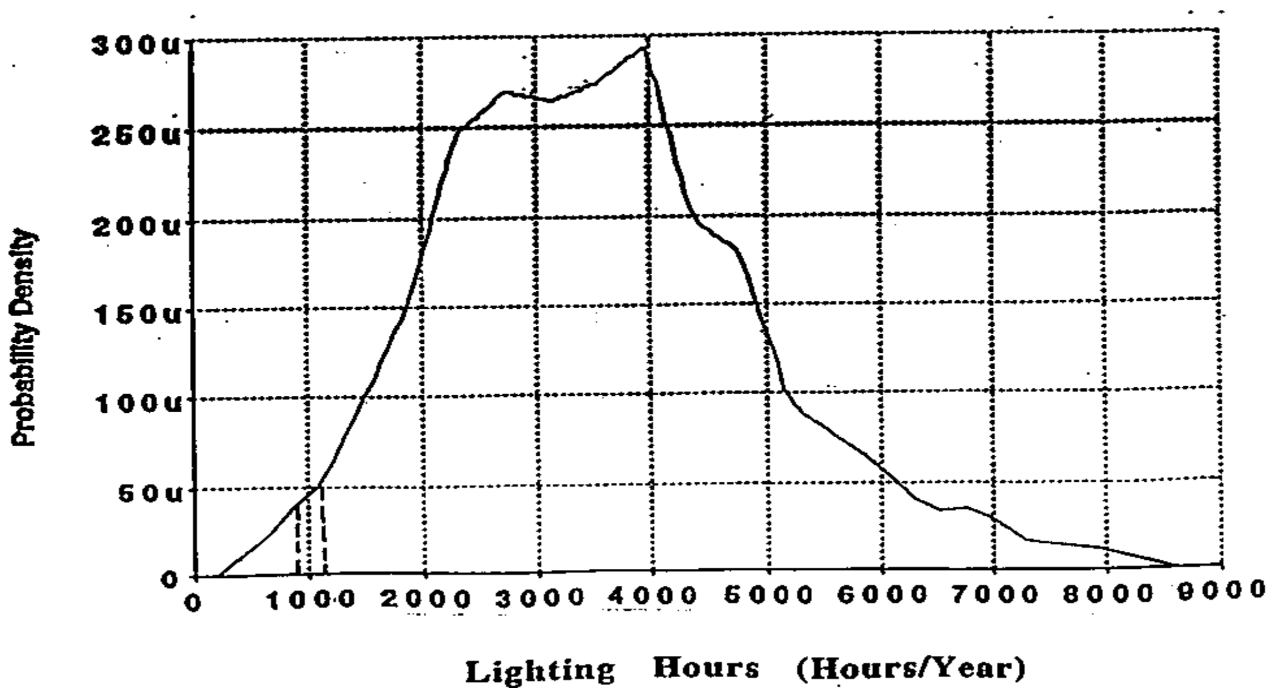


Figure 13. Sensitivity of PAYBACK To Lighting Hours
Two Lamp F40T12/ES

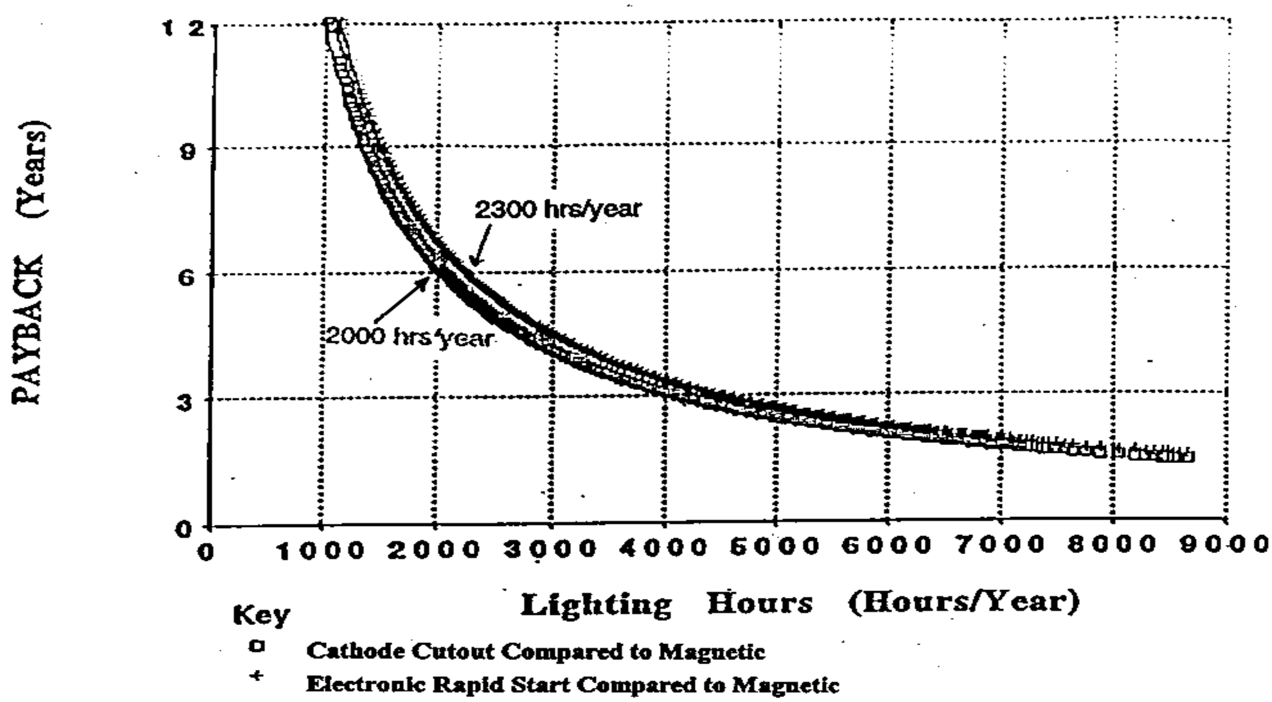


Table 4. Payback by Percent of U.S. Ballasts in Commercial Stock Depending on Annual Lighting Hours
(Two Lamp F40T12/ES)

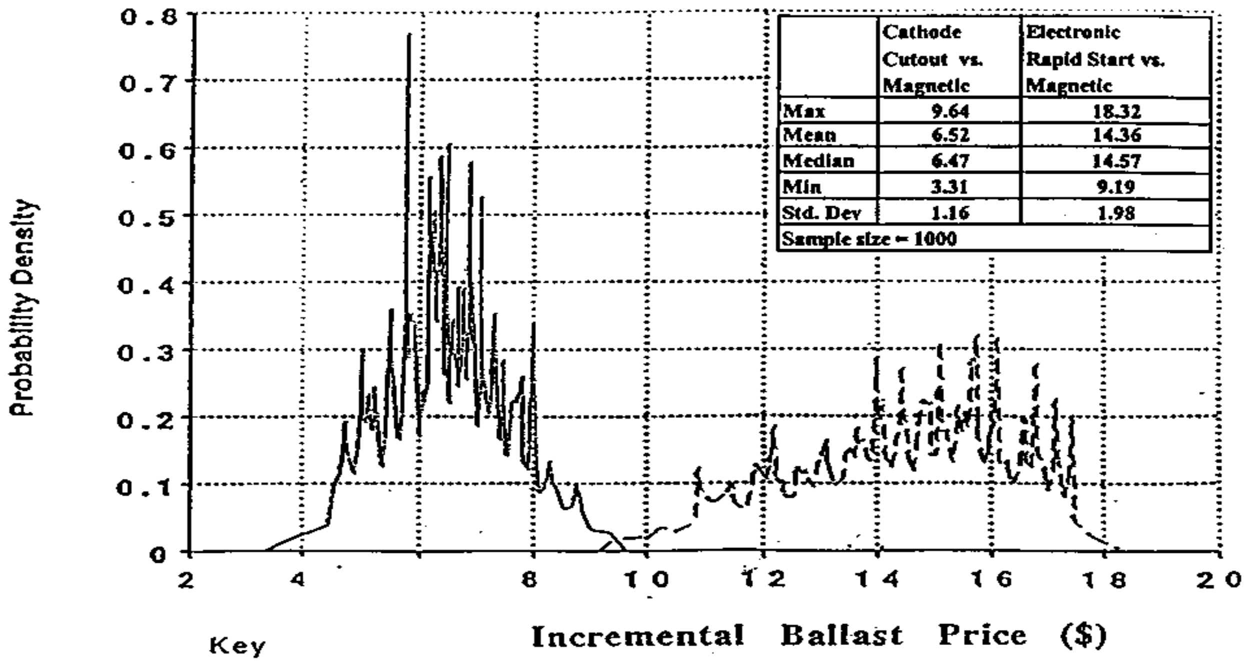
Payback Less Than (Years)	Cathode Cutout Compared to Magnetic	Electronic Rapid Start Compared to Magnetic
3	31%	24%
6	86%	84%
9	96%	95%
12	98%	97%

Table 5. Distributions of Ballast Consumer Prices
(2F40T12/ES)

Design Options	2F40T12/ES
Magnetic	Triangular (11.20, 12.44, 14.31)
Cathode Cutout	Triangular (16.97, 18.86, 21.69)
Electronic Rapid Start	Triangular (21.71, 28.94, 30.39)

NOTE: Three parameters in a Triangular distribution are minumum, likeliest, and maximum.

Figure 14. Incremental Distribution of Ballast Consumer Prices in Commercial Sector (2F40T12/ES)



Key
Cathode Cutout Compared to Magnetic
Electronic Rapid Start Compared to Magnetic

Table 6. Cumulative Probability of Incremental Ballast Price (2F40T12/ES)

Incremental Ballast Price Less Than ($)	Cathode Cutout vs. Magnetic	Elec. Rapid Start vs. Magnetic
2	0%	-
4	2%	-
6	33%	-
8	90%	0%
10	100%	2%
12	-	15%
14	-	40%
16	-	76%
18	-	99%
20	-	100%

Figure 15. TOTAL LCC CHANGE ($): Two Lamp F40T12/ES

Net Savings or Net Costs Depend on Incremental Ballast Price

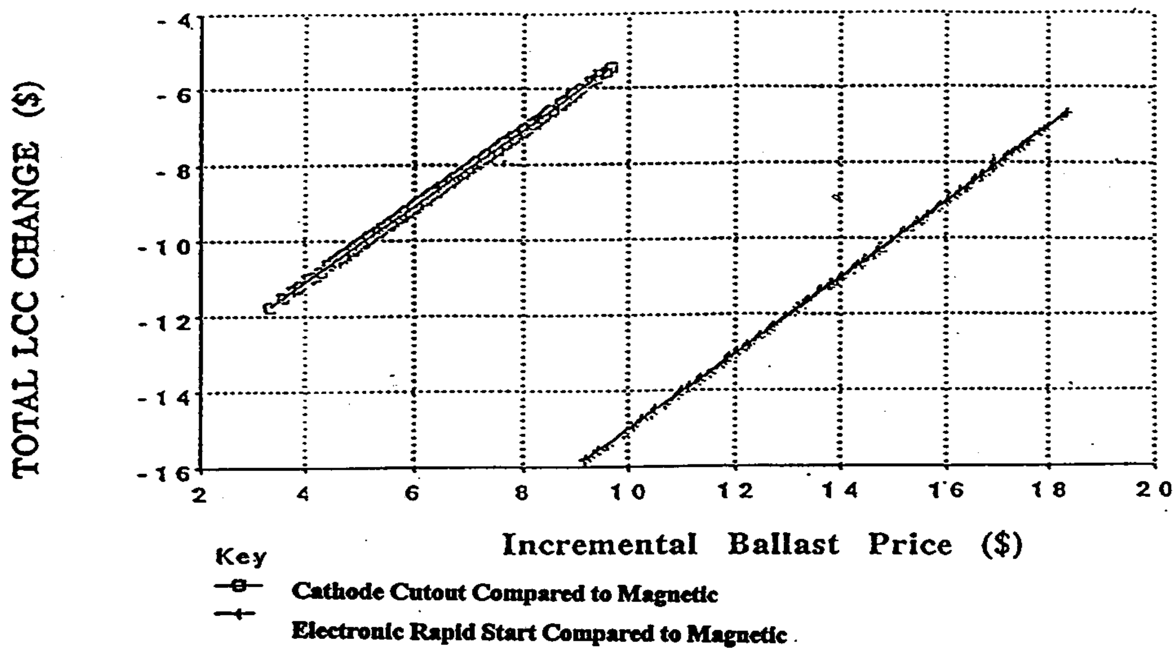


Figure 16. Sensitivity of PAYBACK To Incremental Ballast Price

Two Lamp F40T12/ES

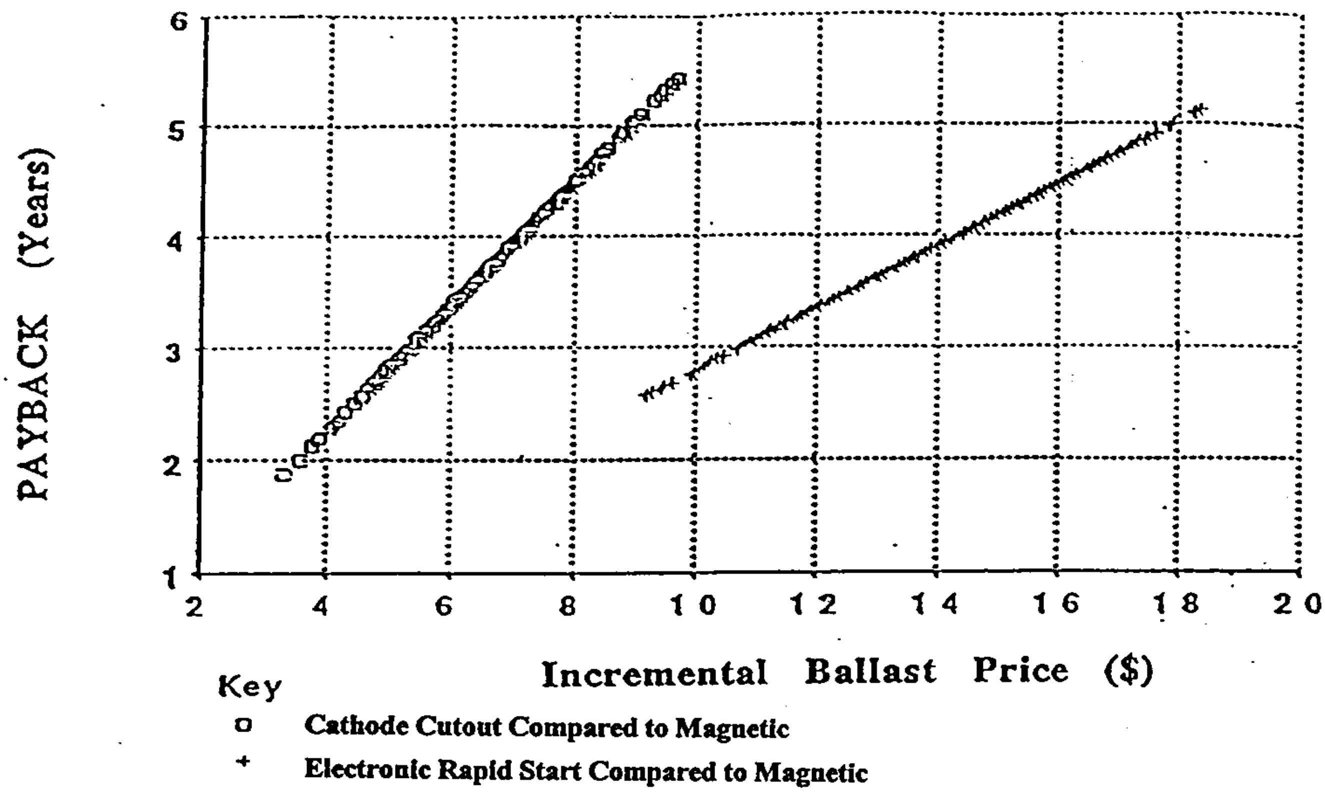


Table 7. Payback by Percent of U.S. ballasts in Commercial Stocks Due to the Variability of Incremental Ballast price (Two Lamp F40T12/ES)

Payback less than (Years)	Cathode Cutout vs. Magnetic	Elec. Rapid Start vs. Magnetic
2	0.5%	0%
3	18%	4%
4	69%	44%
5	97%	99%
6	100%	100%

Figure 17. Lifetime of Ballast (Four Foot Lamp)

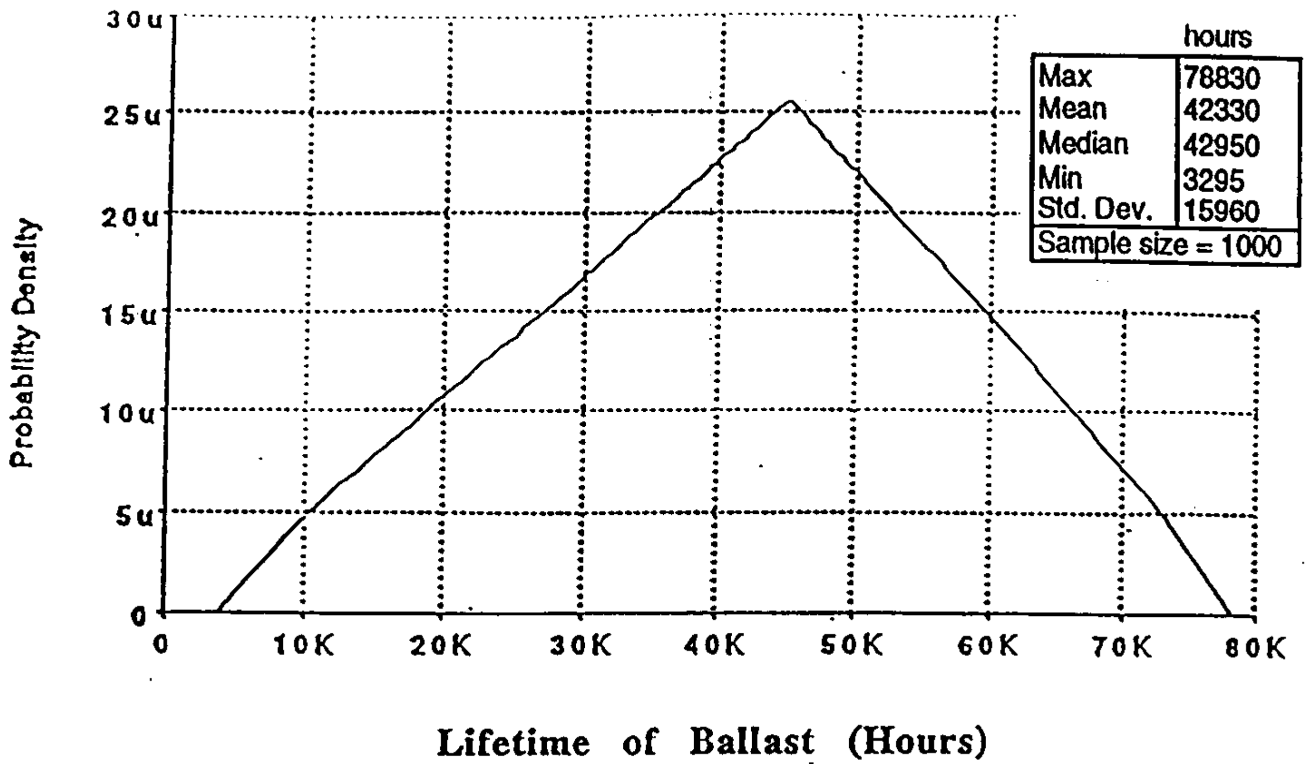


Figure 18. Cumulative Probability of Lifetime of Ballast

(Four Foot Lamp)

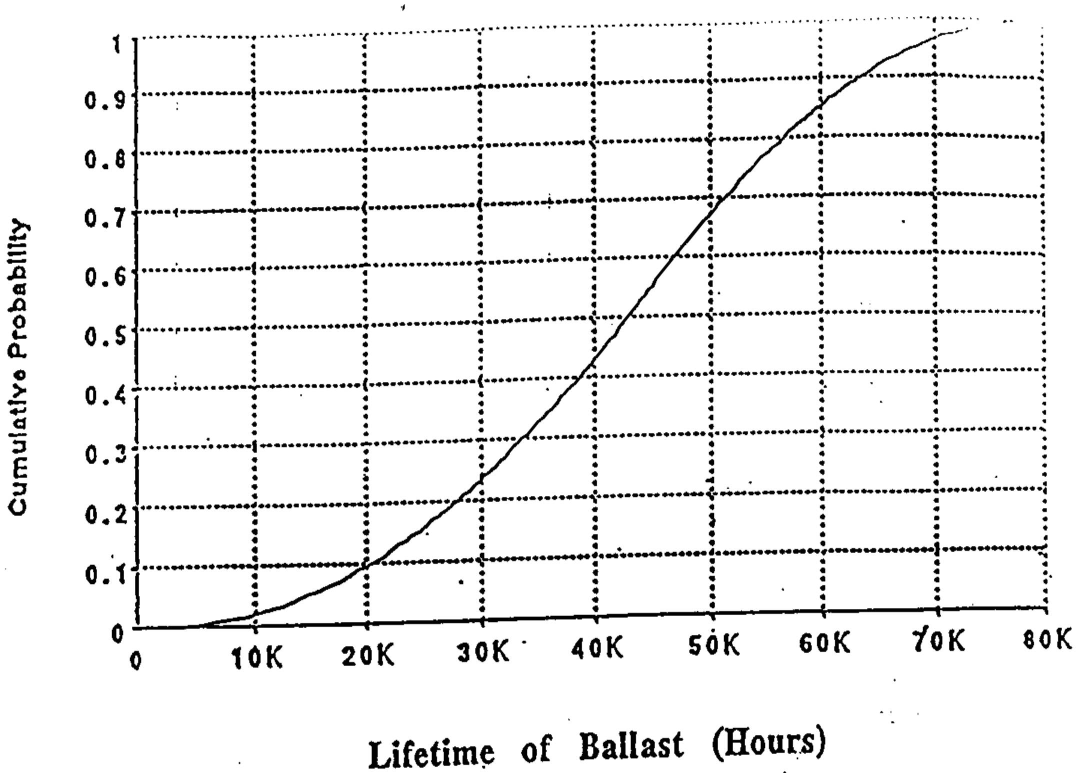
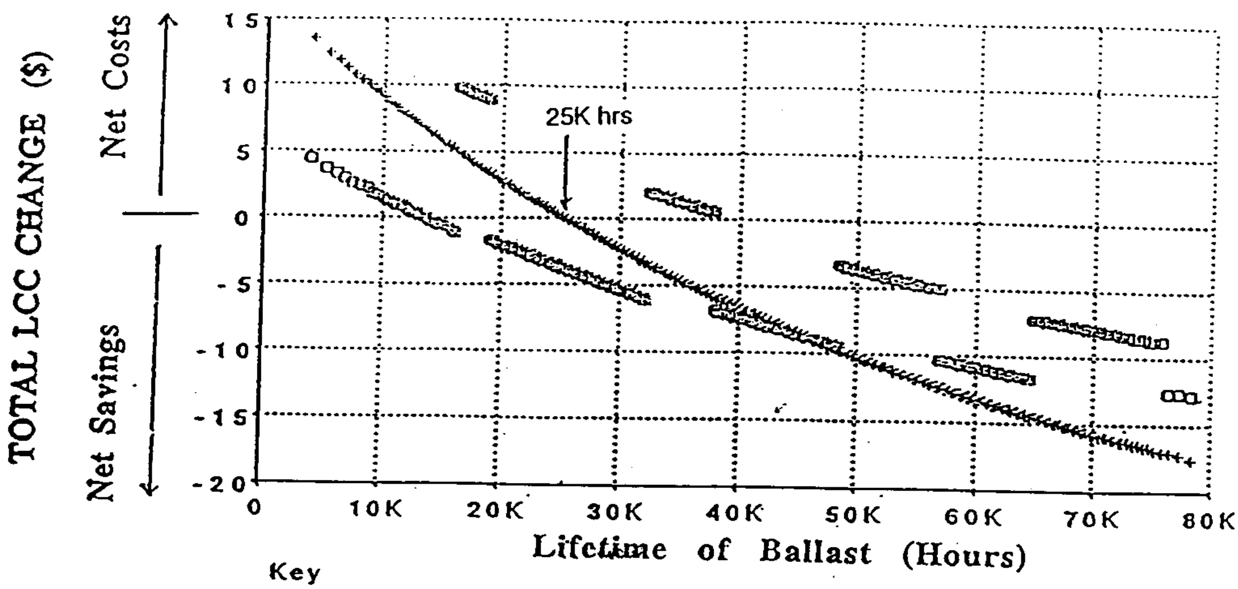


Table 8. Cumulative Probability Table of Ballast Lifetime

Ballast Lifetime Less Than (Hours)	Percent of Ballasts in Commercial Stock
10,000	2%
20,000	10%
30,000	24%
40,000	43%
50,000	67%
60,000	85%
70,000	96%
80,000	100%

Figure 19. TOTAL LCC CHANGE ($): Two Lamp 2F40T12/ES

Net Savings or Net Costs Depend on Ballast Lifetime



Key

□ Cathode Cutout Compared to Magnetic

+ Electronic Rapid Start Compared to Magnetic

Figure 20. Cumulative Probability of Total LCC Change Depending on Ballast Lifetime (2F40T12/ES)

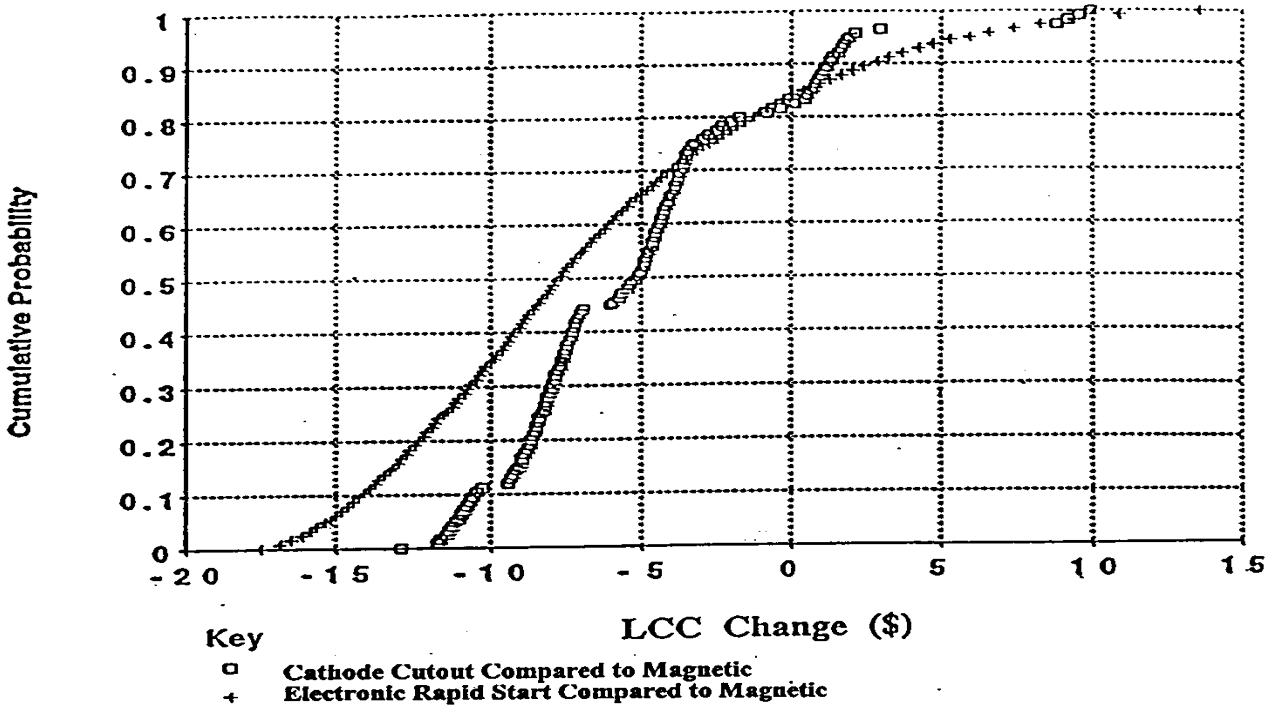
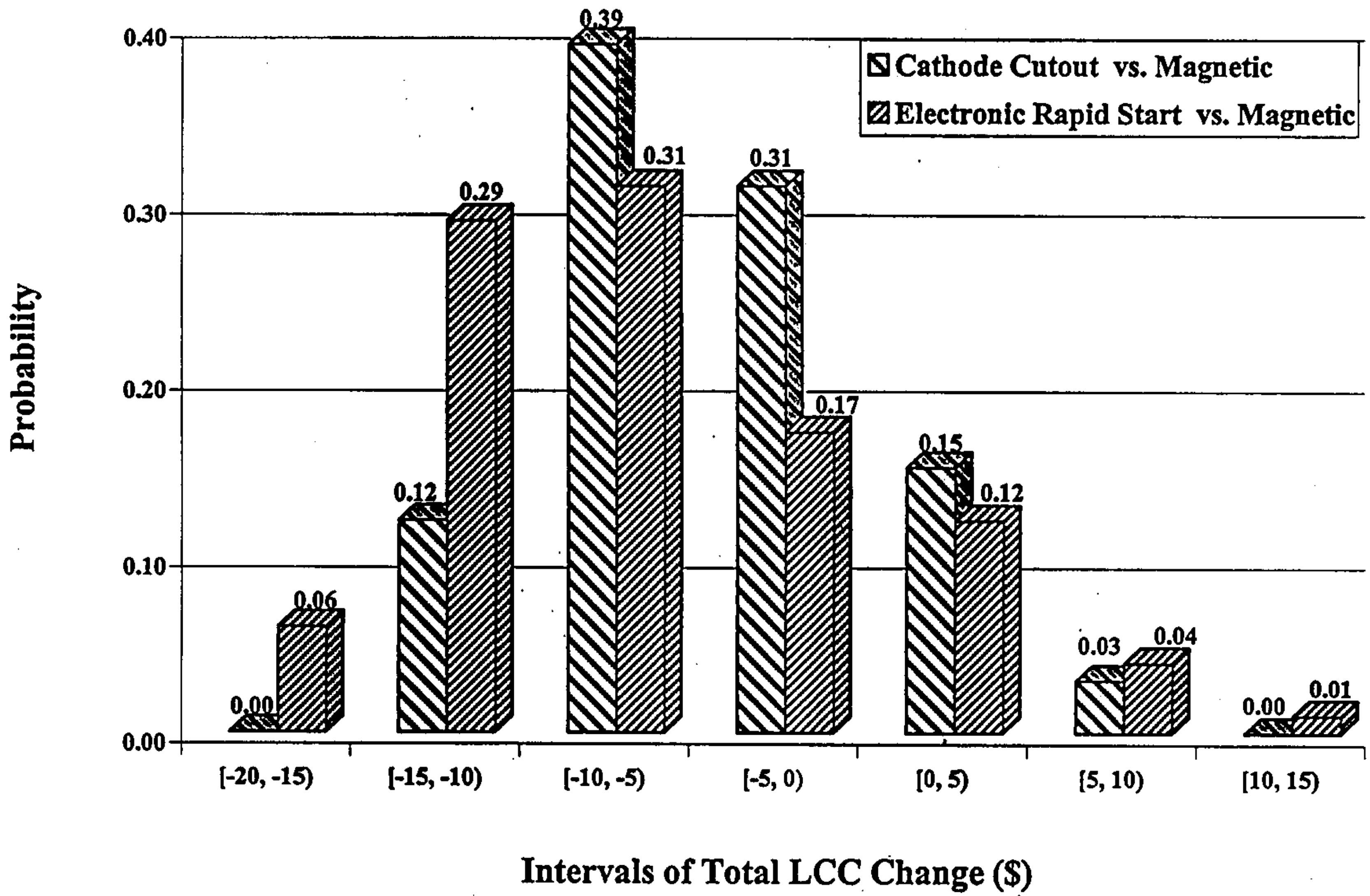


Figure 21. Probability of Total LCC Change by Intervals Depending on Ballast Lifetime (2F40T12/ES)



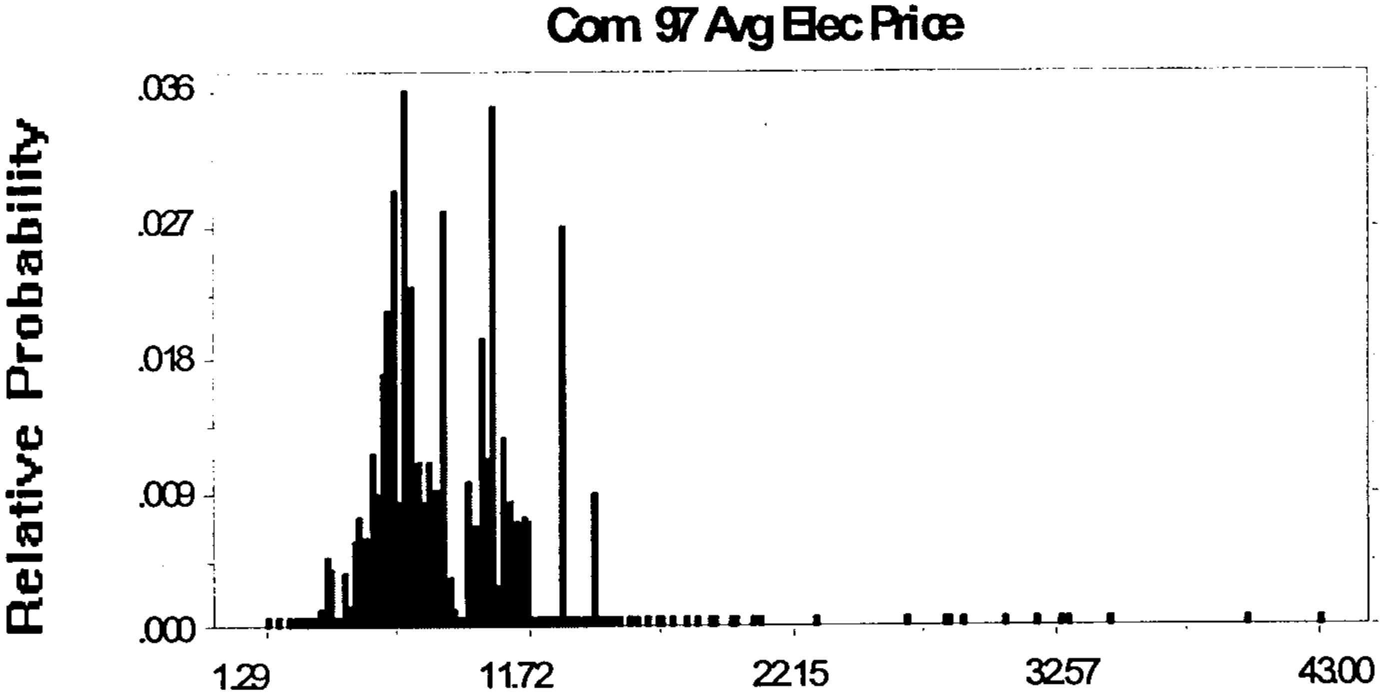


Figure 22 (A). Distribution of 1997 Average Commercial Eectricity Prices

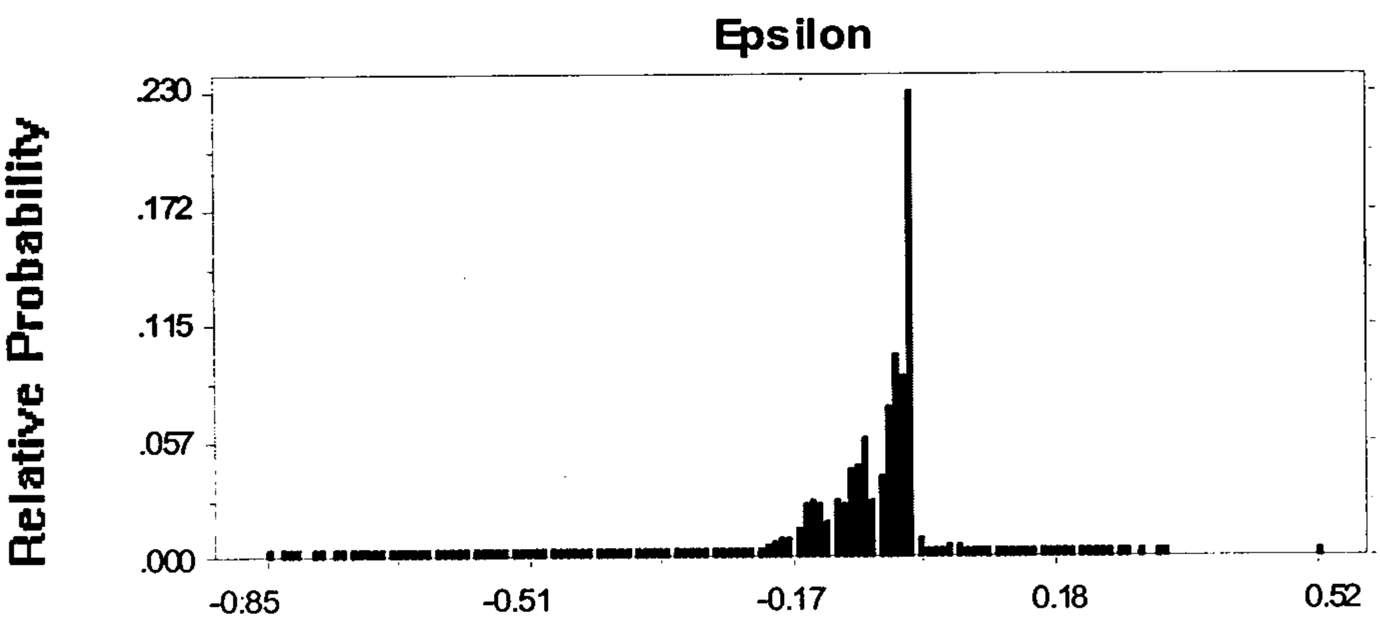


Figure 22 (B). Distribution of Epsilons

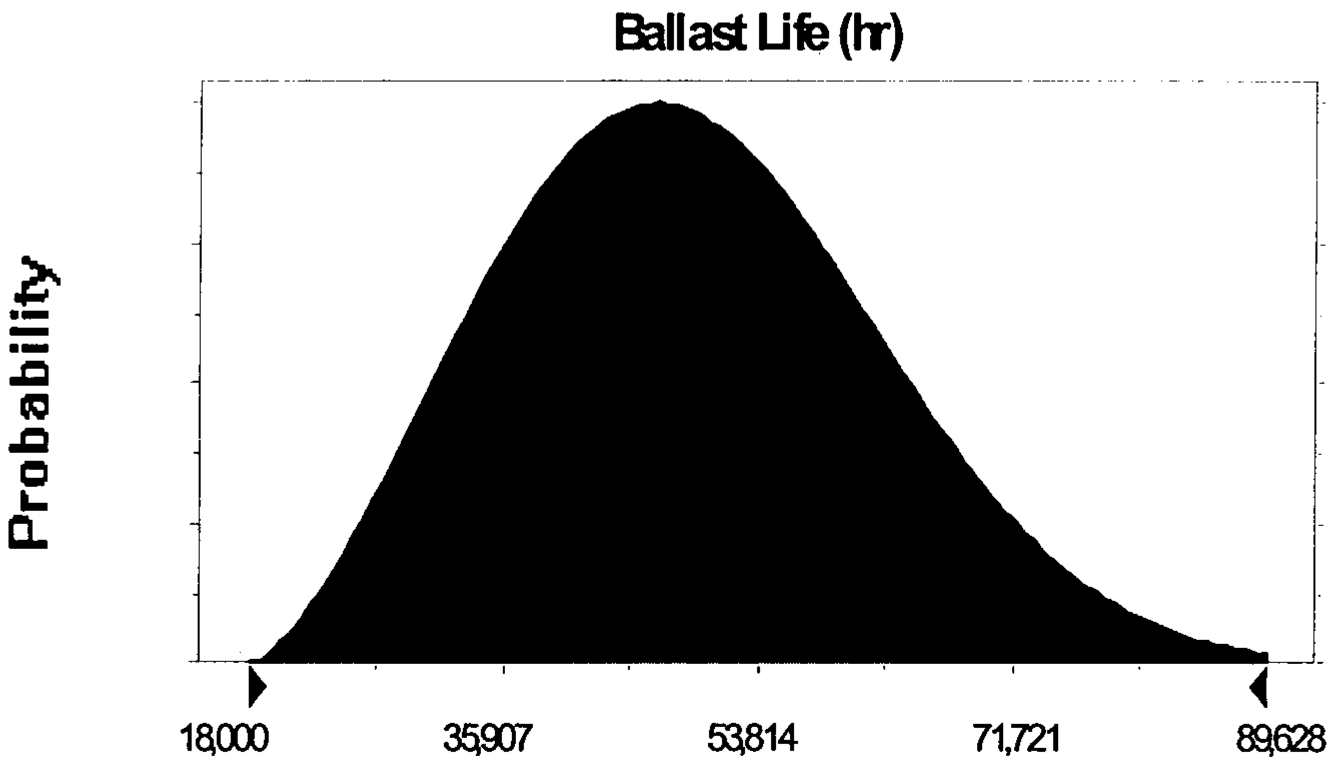


Figure 23. Ballast Life Time (Weibull Distribution)

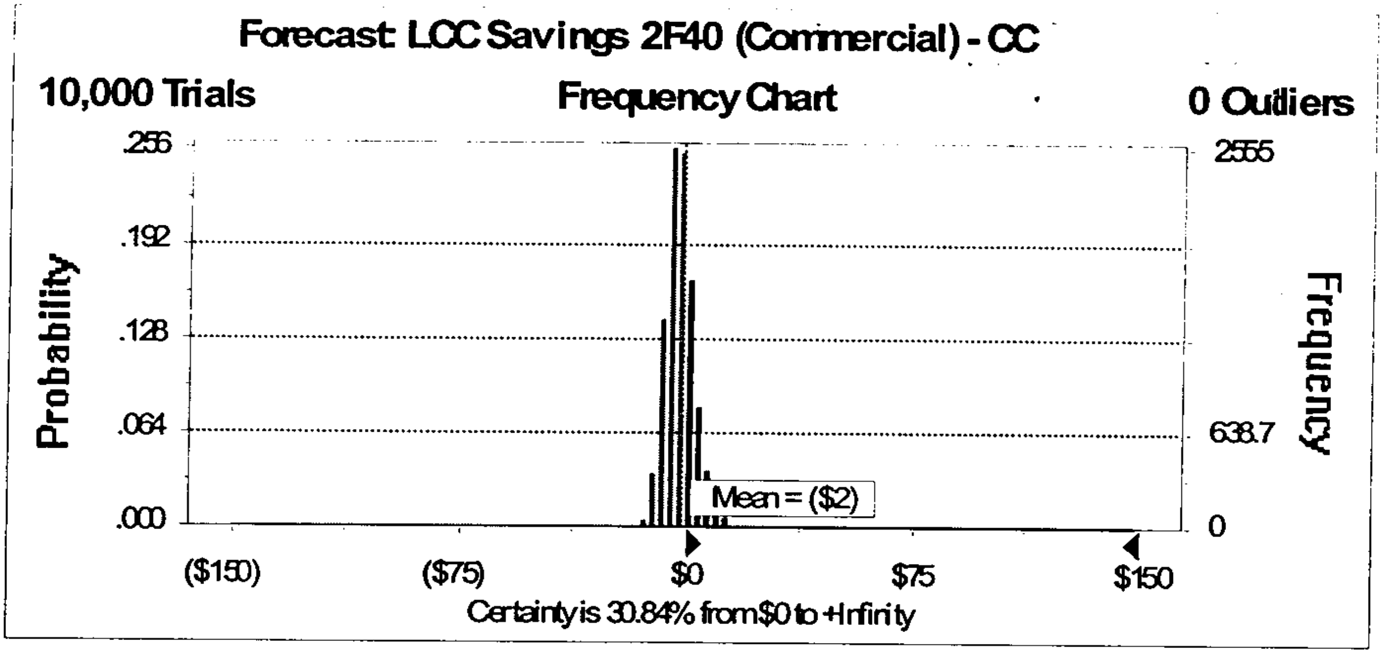


Figure 24. Life-Cycle Cost Savings for 2F40T12 CC in Commercial Sector

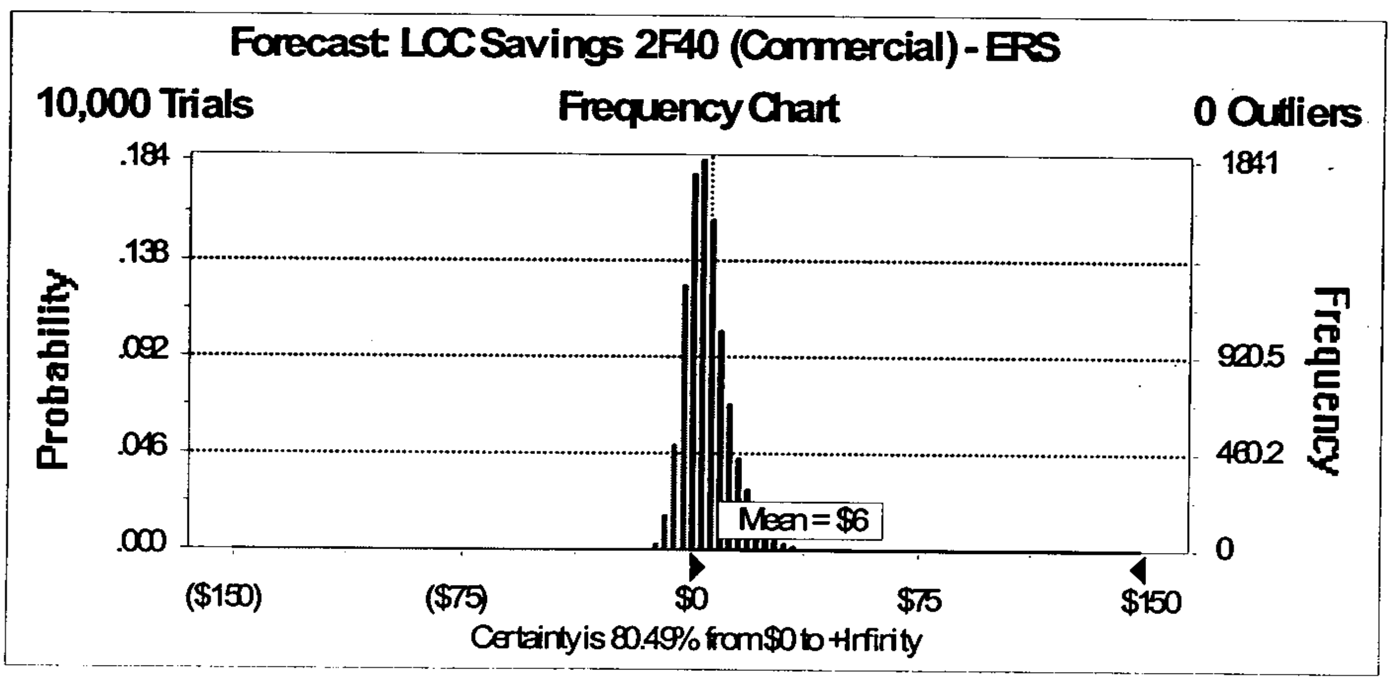


Figure 25. Life-Cycle Cost Savings for 2F40T12 ERS in Commercial Sector

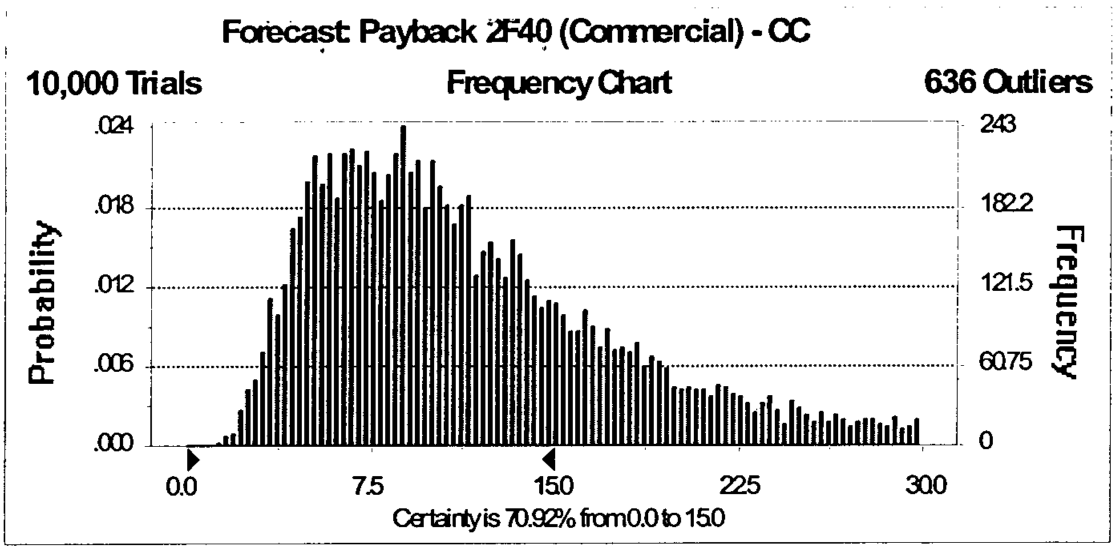


Figure 26. Payback Distribution for 2F40T12 CC in Commercial Sector

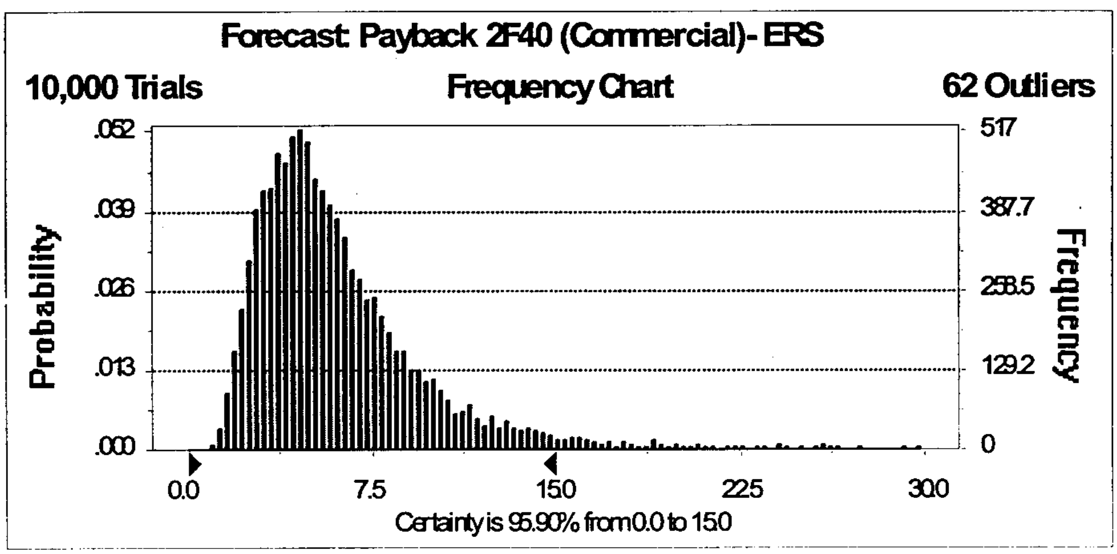


Figure 27. Payback Distribution for 2F40T12 ERS in Commercial Sector

Figure 28. Relative Importance of the Revised Inputs to LCC Changes

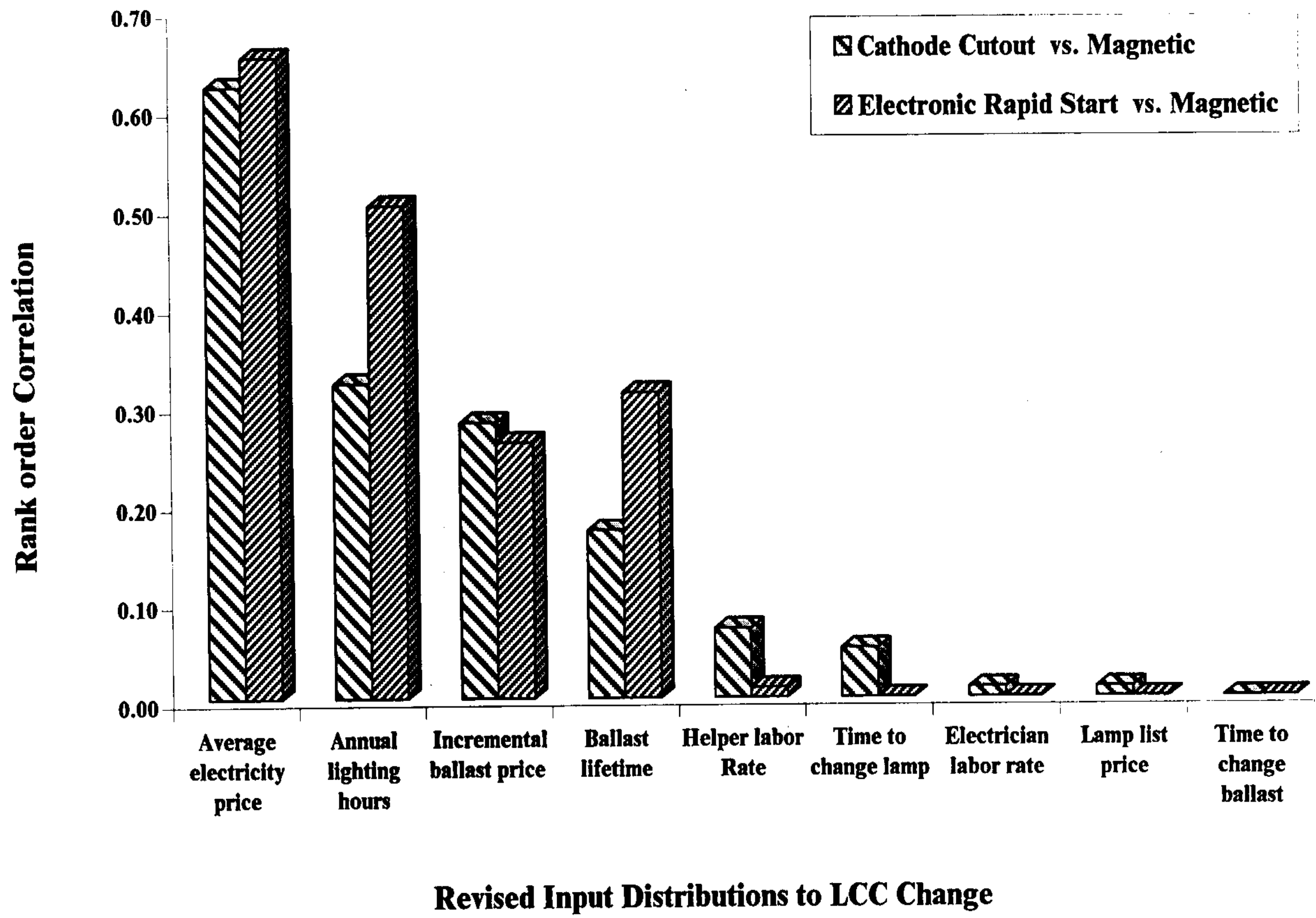


Figure 29. Relative Importance of the Revised Inputs to Payback